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Oceanography of the Chilean Patagonia

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ABSTRACT

Chilean Patagonia is one of the most extended fjord regions in the world that covers nearly 240,000 km^2 with an extremely complex coastline and topography in one of the least densely populated areas of the country (1–8 inhabitants every 10 km^2). In recent years, the area has been undergoing somewhat intense pressure since several commercial projects in hydroelectricity, tourism, and commercial salmon and mytilid cultures have been developed, or are in progress. Concomitantly, several large research programs have been devised to study the physical, chemical, and biological environment of Patagonia, such as the CIMAR FIORDO, and recently COPAS Sur-Austral based at Universidad de Concepcion, that attempts to close the bridge between oceanographic knowledge and its use by society.

In this introductory article we summarize the collection of papers comprising this Special Issue of Continental Shelf Research. These papers deal with aspects of regional oceanography and geology, inorganic and organic geochemistry, ecology of pelagic and benthic organisms, and past changes in productivity.

1. Introduction

Chilean Patagonia is one of the most extended fjord regions in the world, located on the southeastern border of the Pacific Ocean extending from 41.5°S (Reloncaví Fjord) to 55.9°S (Cape Horn), covering 240,000 km^2 (Fig. 1), and composed of many islands, peninsulas, fjords, and channels that leave the landscape with a rugged coastline of about 1000 km in a straight line, but of ca. 84,000 km of coastline, 20-fold longer than the Chilean continental coastline (Silva and Palma, 2008). This is an area of low population density ranging from one inhabitant every 10 km^2 (such as the Arturo Prat province) to 0.8 inhabitants per square kilometer (Aysen region).

The Chilean fjords and channels receive fresh water from local rivers, surface runoff, and groundwater flows fed by high rainfall (100–700 cm year^{-1}, MOP-DGA, 1987), and glaciers. Rivers Baker (1,133 m^3 s^{-1}), Pascua (753 m^3 s^{-1}), and Bravo (112 m^3 s^{-1}) are located at ca. 48° S; Aysén (283 m^3 s^{-1}) and Cisnes (253 m^3 s^{-1}) at ca. 45° S; Puelo (678 m^3 s^{-1}), Petrohué (278 m^3 s^{-1}) flowing into the Reloncaví fjord, and Yelcho (363 m^3 s^{-1}) into the Corcovado Gulf (Dirección General de Aguas de Chile, www.dga.cl). Temperature ranges between 5.5 °C at 54°S and 11 °C at 42°S (Miller, 1976).

Fjords are high latitude estuaries that are usually longer than they are wide, with relatively deep water columns and presenting steep walls. They were formed by erosion due to the advancement and retreat of glaciers during the last ice age, and filled with seawater during high sea level in the interglacial. Fjords undergo estuarine circulation due to the occurrence of a river discharging at their most upstream point. The irregular bottom topography and the presence of several sills enhances deposition of sinking particles and may slow down circulation. Even though low oxygen concentration has been detected (ca. 100 μM), in the Chilean fjords, no anoxic basins have been found. That contrasts with some fjords in the Oslofjord and the Framvaren in Norway, and in Saanich Inlet in British Columbia.

The Chilean Patagonia is also characterized by the presence of five large Ice Fields (Northern Patagonian, Southern Patagonian, Muñoz-Gamero Peninsula, Santa Inés Island, Darwin Mountain), considered valuable fresh water reservoirs of worldwide importance (for instance, the Southern Ice Field provides ca. 3000 m^3 water s^{-1} to the ocean, and it is world's third most important reserve of fresh water after Antarctica and Greenland). These ice fields are unique at these latitudes (46–48°S) and are conserved due to atmospheric and oceanic circulation patterns. Pickard (1971) pointed out that the influence of glaciers on oceanographic features is more pronounced in southern Chile than in the fjords of Alaska and British Columbia. For instance, Secchi disc values of only 1 m, affected by glacial silt, were measured up to 80 km from the

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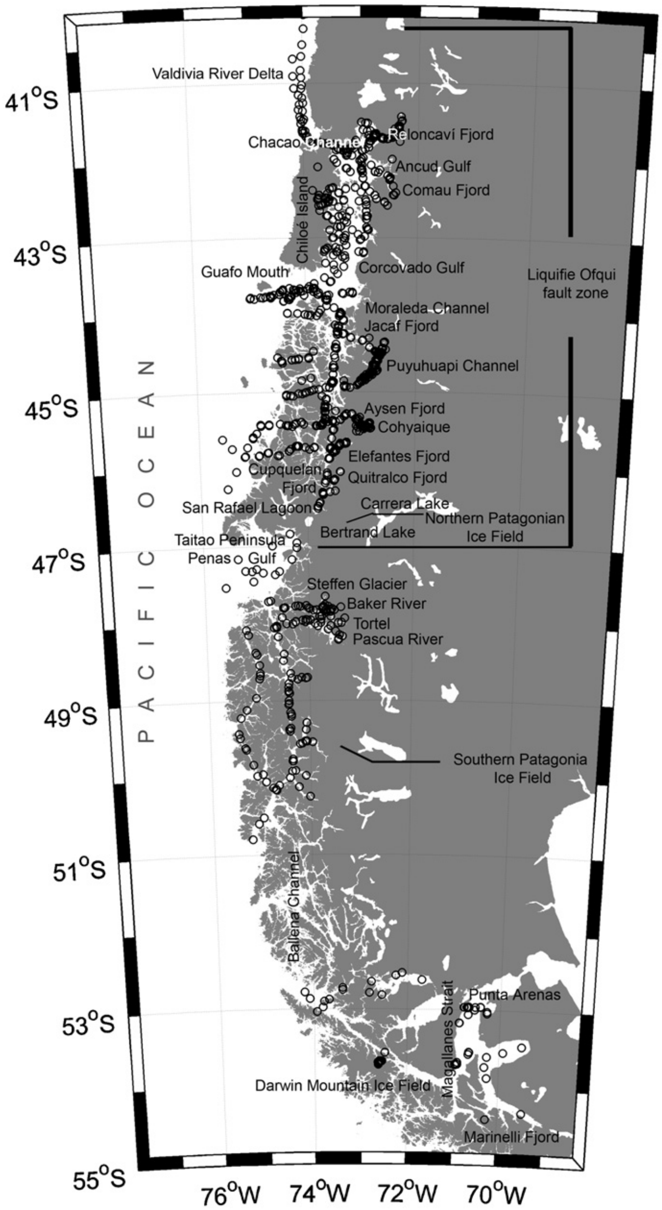

Fig. 1. Map of the Chilean Patagonia showing the observation sites included in the articles of this Special Issue.

glacier inflow area in the Baker Channel in southern Chile, whereas in the northeast Pacific those values are found only up to 20 km from the inflow.

The combination of the significant volumes of fresh water from ice fields, astounding landscape, and clean semi-enclosed water bodies is increasingly attracting the attention of new stakeholders including developers associated with the hydroelectric, tourism, and salmon aquaculture industries. Increased anthropogenic presence and more vigorous economic developments are beneficial to the local Patagonian population due to new infrastructure and jobs; however, these activities also represent serious challenges to the Chilean Patagonia natural heritage.

The development of Patagonia needs to be supported by solid scientific knowledge and a thorough understanding of the limitations imposed by the fragile nature of the mostly pristine Patagonian ecosystems. Constraining boundaries and limits to human intervention is fundamental if we are to avoid irreparable damage to world's first class environmental surroundings. In-Depth knowledge of both terrestrial and aquatic Patagonian ecosystems is however rather scarce. This Special Issue of Continental Shelf Research devoted to the Oceanography of Chilean Patagonia, complements previous efforts of synthesis carried out by the Chilean *National Oceanographic Committee* (Silva and Palma, 2008) and the *International Geosphere–Biosphere Program* (Pantoja et al., 2010), brings updated publications (scientific papers rather than review chapters) that contribute with up to date knowledge about the functioning of the Patagonian ecosystem.

A substantial portion of the oceanographic data shown here were collected during the scientific cruises of the CIMAR Program of the National Oceanographic Committee of Chile (CONA)—a study that started in 1994 of the austral channels and fjords located in Chile from Puerto Montt (42°S) to Cape Horn (56°S). This Program of *Marine Research Cruises in Remote Areas* (CIMAR) was developed in order to fill the information gap "where information on the marine environment has a strong influence on the sustainable socioeconomic development of the local communities and the country" (Silva and Palma, 2008).

2. Summary of papers

The Chilean Patagonia is under the influence of first order tectonic activity that includes the only known triple junction, a location where two tectonic plates that are separating (Antarctic to the south, and Nazca to the north) are being subducted by a third plate (South American), and several geological faults. One of the most important is the Liquiñe–Ofti fault that runs from Liñique (near Villarrica, 39.4° S) to the Wager island in the Golfo de Penas (47° S). As a result, the area is highly active from seismic and volcanic points of view and recently has undergone important volcanic eruptions (Hudson, Chaitén) and earthquakes, which, in the case of the Aysén fjord, was followed by a tsunami with loss of lives in 2007. Legrand et al. (this issue) present valuable seismological data related to a sequence of earthquakes that occurred along the intra-arc region of southern Chile. This seismic sequence is potentially related to the interaction between the tectonics of a large strike-slip fault system and fluid/magmatic activity. The authors suggested that the seismic crisis was associated with a major arc-parallel fault zone, which accommodates part of the margin-parallel component of plate convergence at an oblique subduction zone, arguing that the seismic swarm may result from fluid and tectonic activities. The main conclusion for the local structure is that the seismic crisis was associated with a pull-apart structure with seven monogenetic cones.

Even though the Chilean fjord ecosystem, along with New Zealand are major fjord systems in the subpolar margin, many uncertainties are present regarding freshwater influence on the local oceanography, and subsequently on the biological and chemical impact on the coastal ocean. In order to address these issues, Calvete and Sobarzo (this issue) analyzed hydrographic information from CIMAR-FIORDO cruises carried out between 1998 and 2001, and evaluated the influence of fresh water carried out by some of the major rivers in Patagonia (Pascua, Ventisquero, Queulat, Cisnes, Aysén, Lagunillas, Huemules, and Exploradores). By calculating the equivalent height of fresh water they concluded that the brackish layer was found to be 1 to 15 m thick, with horizontal extensions on the order of 100 km.

Copious woodland vegetation and water runoff results in large but as yet unquantified amounts of organic debris being washed to fjords and channels. Hinojosa et al. (this issue) compared floating objects on the sea surface along two different types of coasts: central-southern Chile and the Patagonian fjords. The floating objects, with accumulation areas being more common in the fjord zone, were classified into three categories: floating marine debris (mainly plastic objects and Styrofoam), wood (trunks and branches), and floating kelps (*Macrocystis pyrifera* and *Durvillaea antarctica*). Most importantly, Hinojosa et al. indicated that floating marine debris abundances generally corresponded to the distribution of human activity, and were the highest in the inner Sea of Chiloé, where aquaculture is intense. Hinojosa et al.'s results emphasize the fact that floating debris sources are locally distributed, whereas floating algae may be frequently dispersed over greater distances.

The fresh water influence was also addressed from the point of view of allochthonous subsidies of material to the fjord water column. Vargas et al. (this issue) showed that riverine freshwater contributed a significant amount of dissolved silicon but neither nitrate nor phosphate to the brackish surface layer of the fjord ecosystem. However, carbon ingestion rates measured in the river plumes indicate that terrestrial carbon was equivalent to 20–50% of copepod body carbon during low food periods, suggesting a significant subsidy of terrigenous carbon to the coastal ecosystem. This observation was confirmed with C-stable isotope mass balance of suspended particulate organic carbon, and the presence of fatty acid terrestrial biomarkers in the water column.

A totally different approximation was taken by Montero et al. (this issue) to show that alloctonous carbon may be also fueling this coastal environment. In the extensive Reloncavi Channel, they observed that the observed unbalance between primary production and community respiration during winter could be explained by the input of external carbon. However, prokaryotes consume most of photosynthetically produced organic matter most of the year. In addition, lower primary production measured during winter was associated with small phytoplankters that consequently were reflected in minimal sedimentation rates. In relation to the seasonal cycle of productivity in the Reloncaví Fjord, Montero et al. (this issue) determined that seasonal changes in the direction and intensity of winds, along with a late-winter improvement in light conditions, appear to play a pivotal role in the timing of phytoplankton blooms and potentially modulate productivity cycles in the region.

Other mechanisms for microorganisms to cope with a varying environment in the fjord ecosystem was revealed by Czypionka et al. (this issue), who studied mixotrophy (the combination of autotrophic and heterotrophic nutrition in the same organism) by measuring bacterivory rates of phototrophic and heterotrophic protists inhabiting a Chilean Patagonian fjord ecosystem. While mixotrophy was nearly absent during austral spring and summer, this process was relevant during austral winter, representing a second niche for mixotrophs during food-limiting conditions.

González et al., (this issue) presented compelling evidence for the complex interplay of topography (sills), solar radiation, and freshwater discharges on plankton structure and carbon fluxes in the fjord area. By examining plankton variability in the N–S oriented Moraleda Channel (42–47°S area, they observed that in winter, even though nutrient concentrations were high throughout the whole Channel, primary production was low (153–310 mg C m^{-2} d^{-1}), suggesting that reduced light radiation was a limiting factor for productivity. In spring, a conspicuous N–S gradient in primary production was found, with the highest rate (5167 mg C m^{-2} d^{-1}) north of the Meninea sill, and the lowest (742 mg C m^{-2} d^{-1}) in the basin located south of the sill. On the other hand, in the semi-enclosed Puyuhuapi Channel and Aysen Fjord, no significant differences in primary production ($\sim$800 mg C m^{-2} d^{-1}) were found, whereas vertical fluxes of particulate organic carbon were nearly twice as high in spring than in winter (266 vs. 53 mg C m^{-2} d^{-1}).

Biology differs in the study areas. Thus, north of the sill the water column is dominated by the classical food web during spring, whereas a microbial web dominated in winter. The basin located south of the sill was characterized by low primary production and the permanent presence of glacier-derived fresh water containing silt particles in which small diatoms and bacteria dominate.

The relationship between phtytoplankton availability of macronutrients and the physical environment was investigated by Torres et al. (this issue). They elegantly showed that the availability of nitrate and silicic acid in Seno Ballena Fjord in surface waters was due to the aspiration of subpycnocline waters (tidally induced) with high nitrate–DSi ratio, and the input of continental waters with low ratio nitrate–DSi. This interplay explains the dominance of dinoflagellates in the inner fjord in high nitrate at the base of the shallow halocline.

Light is one of the key factors promoting algal growth. Within the fjord and channel ecosystems light reaching benthic macroalgae experiences important fluctuations associated with tidally induced water level changes and suspended particles both of in situ biological production and terrestrial origin. Huovinen and Gómez (this issue) studied the spectral attenuation of solar irradiation in two contrasting coastal environments in southern Chile: in a northern Patagonian fjord (Seno de Reloncaví) and in a coastal environment on the coast of Valdivia. Solar radiation penetrating to depth at both locations was enough to support light requirements for subtidal species with optimal light conditions to saturate photosynthesis Ek being found at the 10–16 m depth range. While light attenuation did not significantly vary between both sites, the light regime showed important variations due to differences in the tidal range. The study also showed that due to the pattern of UV-B penetration, seaweeds living in the upper littoral zone such as the intertidal and shallow subtidal (>3 m) might be at risk.

Palma et al. (this issue) describe the species composition and distribution of Medusae and Siphonophores in the northern section of Patagonia (Chiloé Inner Sea) comparing seasonal differences between winter and spring, providing base line information on the Cnidarian fauna of the region, reporting 41 new records of Cnidarian species for the area. Distribution of organisms is analyzed with respect to regional hydrography along a north south transect, as well as among three depth strata in the upper 200 m of the water column.

Paredes and Montecino (this issue) relate total chlorophyll-a biomass to diversity in size distribution of phytoplankton (H'_{size}). They tested the hypothesis that size class diversity of phytoplankton follows Connell's (1978) Intermediate Disturbance Hypothesis, with high diversity observed when total chlorophyll-a is "intermediate" rather than at the high or low end of the size spectrum. Paredes and Montecino suggested that H'_{size} and phytoplankton biomass were driven by physical disturbances: higher biomass and larger size classes dominated in deeper mixed layers when sufficient light was available, whereas shallower mixed layers with lower light availability presented lower biomass and smaller cell size phytoplankton classes dominated.

The input of fresh water not only impacts circulation in the fjord area, but also may influence the biology of coastal organisms. Castro et al. (this issue) showed that planktonic organisms from different habitats and phylogeny appear to respond to fluctuations in the tidal regime. They found that at a site dominated by tidal mixing and surface stratification during high tides, an increment in larval density was verified during the flooding phases of the tidal cycle. Conversely, a site dominated by vertical stratification, larval density distribution was better explained by variations in semidiurnal sea level. These findings have implications regarding the fate of larvae in the coastal zone since in some cases they may be transported inshore to food-rich areas. Bustos et al. (this issue) investigated the potential relationship between the composition and abundance of ichthioplankton and stratification of the water column in the fjords and channels of southern Chile. During spring in both 2006 and 2008, they observed an inverse relationship between the abundance of species of fish larvae and stratification of the water column, suggesting further that the species Falkland sprat (*Sprattus fuegensis*), rockfish (*Sebastes oculatus*), and hoki

(*Macruronus magellanicus*) do not spawn and nurse in the inner fjords.

Biology of the sedimentary environment was examined by Montiel et al. (this issue) in an area where no information was available before. They studied subantarctic benthic communities in the Straits of Magellan, compared shallow and deep water polychaete assemblages, and observed higher species richness in the shallow areas than the deep assemblages. Using a multidimensional approach, the authors indicate that shallow assemblages of polychaete were associated to biological properties such as density, richness, and biomass, whereas the deep assemblage was associated to physical properties related to sediment features.

Sepúlveda et al. (this issue) used elemental (organic carbon, total nitrogen) isotopic (δ^{13}C, δ^{15}N) and biomarker (n-alkanoic acids from vascular plant waxes) composition of surface sediments as well as local marine and terrestrial organic matter in order to determine the origin of organic matter in the Patagonian fjord and channel ecosystems. The relative contribution of marine and terrestrial sources were estimated using a mixing equation based on these two end members. The storage capacity of marine-derived carbon suggests that the entire fjord system of northern Patagonia, which covers an area of 240,000 km^2, may represent a potentially important region for the global burial of carbon of marine origin. Silva et al. (this issue) investigated the fate of terrestrial material in the fjord area and determined that this material was largely retained within the fjords whereas marine organic matter was dominant in areas such as channels, sounds, and gulfs, exposed to the open ocean. In contrast with Norwegian and Alaskan fjord systems, organic matter of terrestrial origin does not reach open ocean in the Chilean northern Patagonia region.

The biological production of Chilean fjord is influenced by strong seasonal and latitudinal patterns in precipitation, freshwater discharge, glacier coverage and light regime. Correlating present water column properties (primary production and nutrients) and surface sediment characteristics (biogenic opal, organic carbon, molar C/N, bulk sedimentary $\delta^{13}C_{org}$) from the Chilean Patagonian fjord area between 41°S and 55°S has helped to describe the latitudinal patterns of water column productivity and its imprinting in the underlying sediments. Aracena et al. (this issue) using data collected from 188 water column and 118 sediment sampling sites was able to group the Chilean fjord area into four main productive zones: Inner sea of Chiloe (41–44°S) northern Patagonia (44°–47°S), central Patagonia (48°–51°S), and southern Patagonia (Magellan Strait region between 52° and 55°S). A clear north south gradient was observed based on primary productivity with highest values being found in the inner sea of Chiloe and in northern Patagonia associated with higher nutrient and light availability. The lowest productivity values were found near Caleta Tortel, an area that is heavily influenced by glacier melt water and river discharge loaded with glacial sediments. Biogenic opal in surface sediments reproduced the latitudinal gradient in primary productivity and was directly related to water column silicic acid concentrations.

Changes in siliceous export production and the source of organic matter preserved in sediment core MD07-3109H recovered from the Gulf of Ancud, Chiloe Inner Sea (42°S, 72°W) were used to reconstruct siliceous productivity changes (Rebolledo et al., this issue). Sediments were predominantly of marine origin with marine diatoms composing 94% of the total assemblage of siliceous microfossils. Past productivity patterns were also studied in the same location through the study of mass accumulation rates of organic carbon, nitrogen and SiOPAL. The results showed high productivity values between 1863 and 1869 AD followed by a declining trend until 1921 AD. A transition period of fluctuating values between 1921 to 1959 was followed by a decreasing pattern from 1960 to the present that was associated with decreasing precipitation and stream flow of the Puelo river, as well as a warmer and more stratified water column.

This Special Issue represents the most comprehensive collection of scientific papers dealing with regional oceanography and geology, inorganic and organic geochemistry, distribution and ecology of pelagic and benthic organisms, and past changes in productivity. This Special Issue has relevance to future scientists working in the Chilean Patagonia, and provides fundamental scientific information that can be used for comparison to fjord systems around the world.

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