Preface

Oceanographic Processes in Chilean Fjords of Patagonia: From small to large-scale studies

Introduction

Subantarctic ecosystems, such as the inner shelf of southern Chile (41–55°S), are characterized by a complex system of fjords, channels, gulf, estuaries, bays, and are affected by physical regimes that may strongly modulate biological productivity. Rhythms and rates of primary production in these highly fluctuating fjord environments depend to a large extent on the timing and magnitude of nutrient supply and light availability for primary producers. In such complex fjord systems, the interaction between oceanic waters and freshwater from multiple sources (e.g., rivers, surface and groundwater runoff, snow/glacier melting, and precipitation) produces strong vertical and horizontal gradients in salinity, density, organic and inorganic nutrient ratios and light availability (Pickard, 1971; Dávila et al., 2002; Silva and Palma 2006; Jacob et al., 2014). The vertical structure of the water column (stratiﬁed/mixed), modulated by the seasonal and inter-annual changes of the pycnocline may affect biomass and composition of pelagic and benthic assemblages, and ultimately spatial and temporal patterns of carbon fluxes (the “Biological Pump”), and biogeochemical balances in this large region. In addition, the region is particularly vulnerable to climate change and anthropogenic inﬂuences (Fritarte et al., 2010). Remote and large-scale climatic-oceanographic phenomena (e.g., ENSO and Southern Annular Mode) and global climate trends may alter freshwater discharge of large rivers such as the Puelo and Palena, as has also been suggested for the Baker River located between Patagonian Ice ﬁelds and other northern fjords shown by paleo-oceanographic (Sepúlveda et al., 2009; Rebolloso et al., 2011) and dendrochronological studies (Lara et al., 2008). Although changes in climate are expected to alter the regional atmospheric forcing such as the West Wind Drift (Quintana and Aceituno, 2012; Garreau et al., 2013) and the local ocean circulation in this region, including the northward expansion of the subantarctic water, the impact of these changes on physical dynamics, biogeochemical and plankton properties are still unclear. The information presented in this Special Issue (SI) will be important to the understanding and modeling of future changes in the marine carbon cycle in Subantarctic zones off Patagonia.

Main features of the coastal marine ecosystem

The southern region of Chile contains one of the major fjord regions of the world where salty waters of the Subantarctic Surface Water and Modified Subantarctic Waters mix with freshwater from the fjords generating sharp vertical and horizontal salinity gradients (Fig. 1) (Dávila et al., 2002; Acha et al., 2004; Valle-Levinson et al., 2007; Pérez-Santos et al., 2014; Schneider et al., 2014). Consequences of freshwater input are (1) a sizable supply of terrigenous material from large rivers (600–800 m³ s⁻¹), ice melt and rainfall (2000–7000 mm y⁻¹; e.g., colored Dissolved Organic Matter, González et al., 2013; Lafon et al., 2014), particulate organic matter (Sepúlveda et al., 2011), (2) a cold and freshwater layer overlying a salty-warm water layer that would favor small-scale double-diffusive layering processes, quantified for the first time in Chilean Patagonian fjords (Pérez-Santos et al., 2014), and (3) sharp latitudinal and longitudinal gradients of silicic acid due to surface water mixing between nitrate-rich but Si-depleted oceanic subantarctic waters and Si-rich but nitrate depleted continental waters (Aracena et al., 2011; González et al., 2011; Torres et al., 2014).

Biological consequences of these water column processes are evident: the stratifying effect of buoyancy is a key regulator of primary production and biomass, limiting the depth of turbulent mixing and thereby keeping algal cells within the photic zone (Jacob et al., 2014). On the other hand, stratification isolates algae from their principal source of nutrients below the pycnocline and thus may lead to the eventual shutdown of production after short bloom periods. Here, semidiurnal internal waves can increase vertical mixing of deep nutrients toward the surface, through shear instabilities, which would favor primary production for more extended periods than in classical seasonal systems (Ross et al., 2014). In addition, Valle-Levinson et al. (2014) demonstrated the existence (related to twilight) of semi-diel patterns of vertical migrations of euphausiids and decapods, which could be a common strategy in fjords. Furthermore, some of the Patagonian fjords receive significantly higher loads of fine suspended sediments from snow and glacier melt, which may limit the light available for photosynthesis in near-surface waters, and may explain the low biological production found in these fjords (Jacob et al., 2014). Distributions of harmful algal blooms (HABs, such as Chaetoceros convolutus, Alexandrium catenella), known for their significant impact on aquaculture and human health and environmental issues, represent major research challenges in coastal waters of the entire Patagonia marine ecosystem. The approaches used by Paredes et al. (2014) allow us to conclude the importance of extrinsic environmental factors (nitrate, temperature) to explain the regional spatial scale of microphytoplankton groups, while toxic dinoflagellate species dynamics may be related to changes in the
composition of microphytoplankton community at smaller spatial scales.

Vertical migration, feeding, and reproduction of pelagic fish and zooplanktonic populations are also affected to the point that their spatial distribution results from the interaction of fresh and oceanic waters, mainly through the semi-permanent pycnocline observed in fjords and channels. The effect of river outflow was clearly demonstrated by Meerhoff et al. (2014) who pointed out that early and late-stage barnacle larvae were more abundant in waters of low temperature, high oxygen and high chlorophyll, while bivalve larvae were associated with warmer waters of oceanic origin. Population properties such as the ontogenic feeding pattern and distributions of fishes Sprattus fuegensis and Strangomera bentincki, appeared to benefit from taking advantage of short-term food pulses and thus overcoming changes in oceanographic conditions in fjords (Contreras et al., 2014).

**Biogeochemical processes**

Muñoz et al. (2014) and Zapata-Hernández et al. (2014) studied a newly discovered shallow cold seep site with bacterial sulfur mats in a Chilean Fjord. Cold seeps have been studied in many regions of the world, but as the authors point out, this is novel for Patagonian fjords. Stable isotope geochemistry of carbon, nitrogen and water, as well as vent fluid geochemistry helped establish that the cold seeps represent a site of chemosynthetic activity that sustain bacterial sulfur mats and are the source of methane in the water column (Muñoz et al., 2014). In the community associated with the cold seeps, the food web is maintained mainly by photosynthetic primary production, and bacterial filaments of the mat may be incorporated into the diet of some grazers (Zapata-Hernández et al., 2014). These studies characterize the chemical composition of reduced compounds in the vent fluids emanating from the rocks that might help understand the presence of bacterial mats nearby, and the functioning of shallow water reducing systems.

Vertical mixing and the exchange of nutrients among the low-salinity, low nutrient and turbid surface layer and the warmer and more saline subsurface layer are the main drivers of spring pulses in primary production and autotrophic biomass in the inner seas of Patagonia (González et al., 2013). The concentrations of inorganic nutrients show a strong seasonal signal, with high nitrate and orthophosphate concentrations during winter, and lower values during spring, presumably caused by a sharp increase in primary productivity when light availability in near-surface waters increases (Iriarte et al., 2007; González et al., 2011; Torres et al., 2011; Jacob et al., 2014). Oxygen concentrations in the fjords is mostly the result of horizontal advection of adjacent well-oxygenated Subantarctic Waters (5–6 mL L\(^{-1}\)) that represents the major source of oxygen in the deep layers of the inner seas of Patagonia.

Fig. 1. Schematics of important coastal processes considered in this compilation of articles showing geomorphology (glaciers), physical forcing (wind stress, atmosphere–ocean temperature exchange) and distributions of waters of different temperature and salinity in Patagonian fjords. Permanent surface freshwater plumes from the rivers’ watershed, and ice melt from glaciers, on top of warm and salty oceanic waters promote a sharp near surface stratification (halocline and pycnocline) of the water column. Nutrient enrichment of the near surface waters (photic layer) may occur through tidal fronts, tidally induced internal waves, shear instabilities and small scale processes such as double diffusive convection. (Figure credits, Dr. Ivan Peréz-Santos).

Fig. 2. Map showing the oceanic section from 40°S to 60°S off the Patagonia marine system (from World Ocean Database 2013).
The authors suggest that oxygen levels below saturation found near fjord heads were the result of bacterial respiration of autochthonous and allochthonous particulate organic matter, as ocean waters flow towards the continental fjord heads, where near-hypoxic (2–3 mL L$^{-1}$) or hypoxic levels (<2 mL L$^{-1}$), and increasing phosphorus and nitrate concentrations have been reported.

Oceanic effects on Patagonian inner coastal waters

A better understanding of fjord dynamics will require a resolution of meso- and large-scale processes occurring in oceanic waters adjacent to the fjord region. Future studies should focus on the understanding of large-scale oceanic circulation, water masses properties, their dynamics and their effect on the variability of biological productivity and biogeochemical cycling through the water column in the inner continental shelves of Patagonia. Oceanographically, the fjords and channels of southern Chile could be considered as a transitional marine system, influenced by oceanic deep waters of high salinity and nutrients and surface freshwater of low salinity and nutrients (Schneider et al., 2014). Surface estuarine waters have low concentrations of nitrate and orthophosphate with the oceanic Subantarctic Surface Waters being the main subsurface source (Silva and Neshyba, 1979; González et al., 2011; Pérez-Santos et al., 2014). To a large extent, the input of silicic acid (DSi) to surface waters is driven mainly by river runoff through the weathering of continental rocks (Tréguer and De la Rocha, 2013). Thus, strong changes in availability of silicic acid for primary producers may result from fluctuations in freshwater discharges (Torres et al., 2014), which in addition to seasonal processes, may be undergoing longer-term changes associated with global climate trends (Tréguer and De la Rocha, 2013).

Fig. 3. Hydrography and oxygen data collected from 40°S to 60°S. (a) Temperature, (b) salinity, (c) oxygen, (d) oxygen saturation. Water with salinity of ca. 33.5 in the upper 100 m to 50°S is shown in purple. Note the intrusion of subsurface oxygen (3 mL L$^{-1}$, 100–200 m) of Equatorial Subsurface Waters extending southward to 47°S (northern Patagonia section). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Although the studies in this Special Issue focused on the inner seas and fjords of Patagonia, we also provide basic knowledge for a more comprehensive and integrative framework for ecosystem research. Specifically, it has become clear that the importance of large-scale oceanic processes, such as the entrainment of southern/northern water masses into the fjords, their interaction with freshwater discharges, and the effect on the biological productivity need to be addressed. At present, characterization of the deep oceanic region south of 41°S and how it influences the inner shelves of Patagonia still lacks adequate oceanographic information. Available information (Fig. 2; World Ocean Atlas, 2013) indicates that open ocean waters adjacent to the fjords are characterized by marked vertical (surface to 400 m) and horizontal (>100 km) physical and chemical gradients (Figs. 3–5). First, we note a marked contrast between the northernmost section off Patagonia (41°–45°S) and the Antarctic Polar Front (55°S). Average temperature decreases and salinity increases southward until it reaches the Antarctic Polar Front. Second, the northern and central sections off Patagonia (Subantarctic Zone at 41°–50°S) are defined by temperature >10 °C and salinity <34.0 in the upper 100 m (Fig. 3) until they encounter subantarctic waters (55°S). Surface water salinities vary between 33 and 33.7 due to coastal freshwater input from larger rivers along the coast (i.e., the Puelo, Palena and Baker rivers). Freshwater decreases the density of near surface layer and creates a steep horizontal density contrast across the shelf break (Fig. 5). Third, several remotely-formed water masses are present in the subantarctic zone (41°–55°S: Equatorial Subsurface Water, Subantarctic Water, Freshwater Modified Subantarctic Water; Silva et al., 1998), including the Antarctic Polar Front waters characterized by low temperatures (<6 °C), high salinities (33.7–34.5) and oxygen concentration above 6 ml L⁻¹ (Fig. 3).

The entire oceanic region adjacent to the Patagonian fjords presents relatively high inorganic nutrient concentrations with pronounced north–south and depth gradients (Fig. 4). Both nitrate and orthophosphate concentrations increased southward in freshwater, in the subantarctic zone and Antarctic Polar Front, with lower surface (<100 m) values (<10 μM nitrate, <1 μM orthophosphate) in the northern-central sections (41–50°S). Silicic acid concentrations increased markedly southward up to 20 μM at the Antarctic Polar Front, with low values (<5 μM) at surface layer along the Patagonian margin (50°S) (Fig. 4). In the region between the Subantarctic zone and the Antarctic Polar Front (50–55°S), we suggest that advection of nitrate and orthophosphate into the near-surface by upwelling of water from below (about 150 m depth) could be important to provide nutrients for phytoplankton growth. However, the region north of the Antarctic Polar Front (50°S) was characterized by low surface silicic acid concentration (<5 μM; Fig. 5) probably due to entrainment of subantarctic currents bringing low silicic acid waters into the southernmost section of Patagonia (Torres et al., 2014). Along the northern coast of Chile in the Humboldt Current System, nutrient availability of surface waters is mainly controlled by the interplay between coastal upwelling (inorganic nutrients source) and microalgal productivity (inorganic nutrients sink). Off the southern fjords, the adjacent oceanic area may control inorganic nutrient availability in the coastal ocean, and although it is beyond the scope of the present

Fig. 4. Depth distribution of phosphate (a), nitrate (b), silicic acid (c) from 40° to 60°S. Waters with relatively low phosphate (<1 μM) and nitrate (<10 μM) in the upper 50 m between 41° to 50°S are shown in blue-purple. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Special Issue, it needs to be resolved if we are to more finely understand mechanisms triggering phytoplankton productivity in the fjord ecosystems of southern Chile.

Summary

The articles of this Special Issue on Oceanographic Processes in Chilean Fjords of Patagonia: from small to large-scale studies are the result of a comprehensive regional assessment, combining capabilities such as synoptic seasonal oceanographic cruises with observations with buoys and sensors of hydrographic, physical–chemical and meteorological variables, all to address process-oriented studies. Environmental features and ecological vulnerabilities were important criteria in the decision to choose to research the Patagonian marine system, given its sensitivity to effects of climate change in a pristine coastal zone that is

Fig. 5. Distribution of surface temperature (a), salinity (b), oxygen (c), phosphate (d), nitrate (e), and silicic acid (f) in the southeastern Pacific Ocean (40–60°C), showing the oceanic spread of coastal freshwater with salinity in the range 32.2–33.7. Note the intrusion of waters with low silicic acid concentration (2–3 μM) extending southwards reaching inner waters at ca. 50°C.
undergoing increasing human development, and is being affected by intensive aquaculture industry (salmon and mussel farms) and other activities such as land-use change and deforestation along the coast. This Special Issue allowed us to integrate research that encompasses organisms of a wide size spectra (bacteria, benthic and pelagic invertebrates, and early life stages of fishes), several types of habitats (headwaters of the forested watersheds downstream to pelagic and benthic coastal marine ecosystems, including shallow water seep sites), as well as governing physical dynamics and chemical processes (hypoxia, macronutrients flux). These results will motivate additional studies in the near future to better understand how this marine ecosystem will respond to climate change and non-climatic multi-stressors, which are major drivers of change of the structure and function of marine food webs. The two major drivers of change in the Patagonian marine ecosystem that need to be understood include: (1) changes in stream flows which will affect the physical dynamics of the water column, and (2) changes in fluxes of macro- and micro-nutrients in the upper layers caused by oceanic currents, atmospheric dynamic, and nutrient discharges due to human activity.

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