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The Sub-Antarctic Beagle Channel marine ecosystem: A regional and comprehensive sentinel of global change

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1. *Historical and scientific background*

This special issue merges results obtained during a scientific expedition along the eastern Beagle Channel (BC) with previously available relevant data from the area. The expedition was conducted from 9-19 November 2019 on board the BIPO "*Victor Angelescu*", a research vessel belonging to the National Institute for Fisheries Research and Development (INIDEP-Argentina). The cruise was the result of collaborative bi-national (Chile-Argentina) diplomatic (Argentinian and Chilean Ministries of Foreign Affairs) and scientific efforts, led by the Austral Center for Scientific Research (CADIC-Argentina) and the Research Center: Dynamics of High Latitude Marine Ecosystems (IDEAL-Chile). In addition, this special issue is enriched with historical data from several research initiatives developed by both countries in the BC area and from other international collaborations, thereby providing a wider and comprehensive vision of the biological, chemical, and physical characteristics of the BC. From a historical point of view, both countries, which share the third longest international border of5,300 km, almost engaged in war in 1979 due to a border conflict in the southeastern BC. This war was averted and subsequently there have been decades of tight and close collaborations and friendly diplomatic, scientific, and social relationships. This special issue reflects these efforts.

2. *The Southern Patagonia (SP) and the Beagle Channel*

The scientific relevance – at regional and global scales - of Southern Patagonia (SP), where the BC is located, is due to multiple climatic, oceanographic and socio-ecological factors because this region is: (i) one of the largest sub-polar freshwater

reservoirs (together with Greenland and the Himalaya Range), (ii) harbors an important biodiversity of marine and terrestrial flora and fauna, and (iii) a key hub of the ocean-atmospheric coupling and ocean water-mass circulation, both of which are partially modulated from the Subantarctic regions (where SP is located). The combined effects of these factors affect the regional and global distribution of heat, dissolved gases and, through the transport of nutrients, the global productivity of the oceans. Finally, SP is one of the most sensitive areas to climate change (CC) and is an important part of the culture and legacy of the original-ancestral people from Chile and Argentina.

The BC is part of SP, and is one of the two natural gateways, the other being the Magellan Strait, connecting the two largest oceans, the Pacific and the Atlantic. This area shows an astonishing geomorphology (fjords, channels, bays, etc.) that resulted from the combined effects of tectonic plates (that turned the N-S direction of the Los Andes Mountains towards an E-W orientation along the BC) and the sculpture-work of glacial activity during geological times. In addition, the demand on ecosystem services supported by the BC from different local and foreign actors is growing. Examples of this are the productive private sector (e.g., salmon farming, tourism, green hydrogen, the commercial exploitation of common resources such as king crab and sardine) and the needs of the regional government-sectors to define uses and regulations of the coastal areas of the region. In this context, a collaborative scientific cruise in the shared, bi-national sector of the BC was considered to be an important and necessary activity that would provide key scientific results as well as provide inputs for decision-makers and public policies of the two countries.

3. *Scientific results*

The set of papers in this special issue highlights the large spatial and temporal complexity and variability of the BC, as well as the strong relationships between the terrestrial and marine environments, and their connectivity in terms of biogeochemical properties with the Atlantic Ocean. Such features emphasize the need to incorporate higher resolution data on the seasonal and interannual behavior of key parameters (i.e., CO_2 fluxes between the atmosphere and the ocean and lateral carbon export to the open ocean, among others), essential to the understanding of the carbon pump functioning in coastal marine ecosystems and the contribution of the ocean marginal areas to the global carbon budget.

The scientific research undertaken in this bi-national effort included disparate areas of knowledge, covering chemical, physical, and biological oceanography patterns and processes, involving different functional groups of the plankton (viruses,

bacterioplankton, phytoplankton, zooplankton, and fish larvae), and different carbon pools, both organic and inorganic, belonging to the dissolved and particulate size-fractions. In addition, key processes, such as primary production, metabolic balance of the plankton community, and downward fluxes of particulate organic carbon (POC) and CO_2 in the water column - among others - were studied and reported under a synergistic and collaborative approach.

4. *Physical, chemical, and biological patterns and trends along the Beagle Channel*

Previous synoptic and modeling results (Giesecke et al. (2021); Cucco et al. (2022)), and references therein), suggest that the BC has a net eastward transport of surface waters, from the Pacific to the Atlantic Ocean. Based on observations from current moorings, Lagrangian drifters and tide gauge measurements, Martín et al. (2023) demonstrate that this pattern is essentially driven by height differences between both oceans, and by the influence of the strong winds (westerlies) in the Antarctic Circumpolar Current. They also describe the presence of a single tidal wave main circulation that propagates along the channel which is constrained by the complex bottom topography and the irregular coastline. These dynamic and bathymetric characteristics determine the presence of large heterogeneities within the Channel, i.e. the MacKinlay Strait, which separates two contrasting sectors in the channel, at the west and east of it. Briefly, the western sector is (i) deeper, (ii) the water surface speed is lower and is more stratified (deep waters flow westward), and (iii) the residence time is longer, than in the eastern sector. These features largely modulate the disparate biogeochemical patterns and processes observed at the zonal level. Furthermore, drifters paths shown by experimental observations suggest a strong influence of BC surface water properties well offshore the mouth of the Channel into the Atlantic Ocean, up to the vicinity of the Namuncura/Burdwood marine protected area, at the south of the Malvinas Islands.

The BIPO *V. Angelescu* cruise allowed complete zonal transects as well as time series sampling at both sides of the MacKinley Strait. Several papers in this special issue focus on the study and comparison of processes in both sub-basins confirming biological and chemical contrasting aspects, consistent with the observed differences in the physical configuration of the environment. Malits et al. (2023b) studied the distribution of the optical and fluorescent properties of dissolved organic matter (DOM) along the Channel in spring, using a variety of chemical and biological indicators. The western sub-basin of the BC showed higher concentrations of chromophoric DOM, high molecular weight material and more recalcitrant DOM, with a decreasing gradient towards the Atlantic Ocean. Accumulation of autochthonous humic-like material in this sector and enhanced concentrations of microbially produced DOM suggest an efficient functioning of the microbial carbon pump fueled

by terrestrial DOM sources. This observation is consistent with the results of Rodríguez-Flórez et al. (2023), that also show a microbial food web driven by terrigenous DOM and nitrates, and the key role of the viral shunt in surface/subsurface waters along the eastern of BC. The authors further hypothesize that the higher residence time of the water favors accumulation of recalcitrant and labile DOM in deep waters via viral lysis of infected cells west of Mackinlay Strait. In addition, particulate organic matter (POM) and sediment POM (SPOM) also play a central role in the dynamics of the lower levels of the marine food web.Bruno et al. (2023a) considered the seasonal contribution of autochthonous (phytoplankton and macroalgae) and allochthonous (terrestrial plants) energy sources available for zooplankton, fish larvae and bivalves. They found that locally produced POM (phytoplankton) and SPOM (macroalgae through detritus accumulated in the sediments) were the main food sources, compared with allochthonous material. Moreover, the energy density of organisms in surface waters during spring, as well as the energy transfer from primary producers to higher trophic levels is higher in the western sub-basin of the BC than in the eastern part (Bruno et al., 2023b). This condition, as shown by Cadaillon et al. (2023), is likely related to differences in the biomass and composition of primary producers and small heterotrophs, where bathymetry, water temperature and macronutrient availability seems to play a key role.

5. *Plankton variability - from viruses to zooplankton*

Malits et al. (2023a) reported high spatial and temporal variability of viruses and pico- and nano-plankton fractions along a transect from the BC to open Atlantic waters, showing a trend of more variability in the biological components of the study area than the physical and chemical parameters. Their results show that, while small-scale processes impacted primarily the variability of phytoplankton (and microorganisms), regional-scale processes were mainly related to physical processes. As noted above, the potential influence of the BC water properties on the offshore area (e.g., Burdwood Bank) was tracked using drifters (Martín et al., 2023). Small spatial and short time scale variability were shown to characterize phytoplankton assemblages, and were related to physical processes, such as changing weather conditions, and biological interactions, such as microzooplankton grazing (Cadaillon et al., 2023).

Harmful Algal Blooms (HABs) have been reported for decades in the region, andSchloss et al. (2023), documented the temporal trend (2009-2013) of the dinoflagellate *Alexandrium catenella* along the whole BC. They investigated the role of water mass transport versus local (physical, chemical and biological) hydrographic conditions during the productive season (spring-summer) as cause of the expansion

of this species from west to east within the BC. Their results support the second of these hypotheses, because the highest toxicity from the species was found in the central sub-basin, which is partially enclosed by topographic sills, and flanked by western and eastern sub-basins. Thus, the bathymetric configuration affects the oceanographic (i.e., longer water residence time) and chemical (e.g., higher nutrient, DOM, availability), and in turn, the *A. catenella* outbreaks.

The larval ecology of the squat lobster, *Munida gregaria*, probably the less known part of its life cycle, was studied by (Presta et al., 2023b). These authors showed an increase in larval abundance (zoeae I-IV and megalopae) in the outer, Atlantic side of the BC during spring and autumn, particularly in the area located immediately east of the Mackinlay Strait, which was characterized by shallow and sharply stratified waters with the warmest bottom temperatures. Thus, the squat lobster larval stages were affected by spatial environmental gradients caused by terrestrial (freshwater runoff and of particulate and dissolved components) and oceanic inputs, which exert an influence on larval cohort dynamics and adult reproduction along the BC.

Carrasco et al. (2023) analyzed the distribution of zooplankton along the BC, comparing the western and eastern sub-basins at different seasons of the year using observations from six oceanographic cruises. They showed that the observed zooplankton patterns were primarily related to biological drivers, specifically with phytoplankton biomass (chlorophyll-*a*), small phytoplankton cells (picoeukaryotes and *Synechoccocus* sp.) and heterotrophic bacteria, and to a lesser extent with the physical structure of the water column. The authors described the development of a herbivore food web in spring-summer, with high phytoplankton biomass and large copepods, which turned to a microbial food web structure in autumn-winter.

Presta et al. (2023a) focused on the study of mesozooplankton composition, distribution and trophic attributes (i.e., baseline resources, trophic positions, isotopic diversity metrics), comparing the two sub-basins. Even though the authors found significant differences in the taxonomic composition between both zones, the trophic attributes did not differ statistically on both sides of MacKinlay Strait. In addition, they suggested limited predation by the squat lobster *Munida gregaria* and fish larvae and concluded that the spring community carbon flow is bottom-up controlled..

6*. Carbon dynamics, water column metabolic balance and export*

Latorre et al. (2023) experimentally investigated the metabolic balance of the plankton community (i.e., the ratio of primary production and respiration), together with field measurements of photosynthesis and marine vs atmospheric carbon dioxide concentrations. Most of the metabolic balance measurements indicated the prevalence of autotrophic conditions. Their results also show that the eastern BC is

a net sink of CO_2 in spring (fugacity values in the water column below equilibrium with the atmosphere), which can be explained by the combined effects of biological activity and the solubility pump. This behavior was highly variable over short scales of space and time, showing marked differences in these parameters between the eastern and western sub-basins. A similar general scenario was observed by Caetano et al. (2023), who did analogous measurements of sea CO_2 and ancillary variables in the Eastern BC in early fall. These authors also calculated the air-sea CO_2 flux and the apparent oxygen utilization (AOU) that is related to the balance between pelagic respiration and primary production. Their results were consistent with those of Latorre et al. (2023), showing that the BC acts as a net sink of CO_2 not only in spring but in fall, and that significant respiration differences existed between the two sub-basins. However, in contrast to Latorre et al. (2023) the authors concluded that the fall dynamics of this gas are mainly controlled by metabolic processes rather than by the solubility pump.

Flores-Melo et al. (n.d.) investigated the downward flux of particulate matter in the vicinity of Yendegaia Fjord, a region strongly influenced by glacier input, and other regions with mainly freshwater input from rivers (east of Ushuaia Bay). They found marked differences in the particle sedimentation between both sites. The POC was dominated by phytoplankton cells, zooplankton fecal pellets and undetermined organic material. In the eastern sector organic matter was mainly consisted of locally produced carbon, while fluxes in the western site were driven by the agglutination of organic matter with inorganic ballast particles of glacial origin. Furthermore, the authors observed significant differences in the composition and contribution of zooplankton pellets, with appendicularians dominating at the western site and pellets of the squat lobster *Munida gregaria* as the most important flux item at the east. Furthermore, the fluxes also showed seasonal differences between sites.

A general feature of the Patagonia region is that the organic matter from terrestrial origin enters the marine environment, affecting the isotopic plankton composition, as for zooplankton in surface waters, reported by Castro et al. (2024). In addition, these authors also conclude that complex processes of lateral inshore-offshore transport of water masses also seems to modulate the presence of zooplankton and its food in fjords (e.g., Baker Fjord) and channels (e.g., BC).

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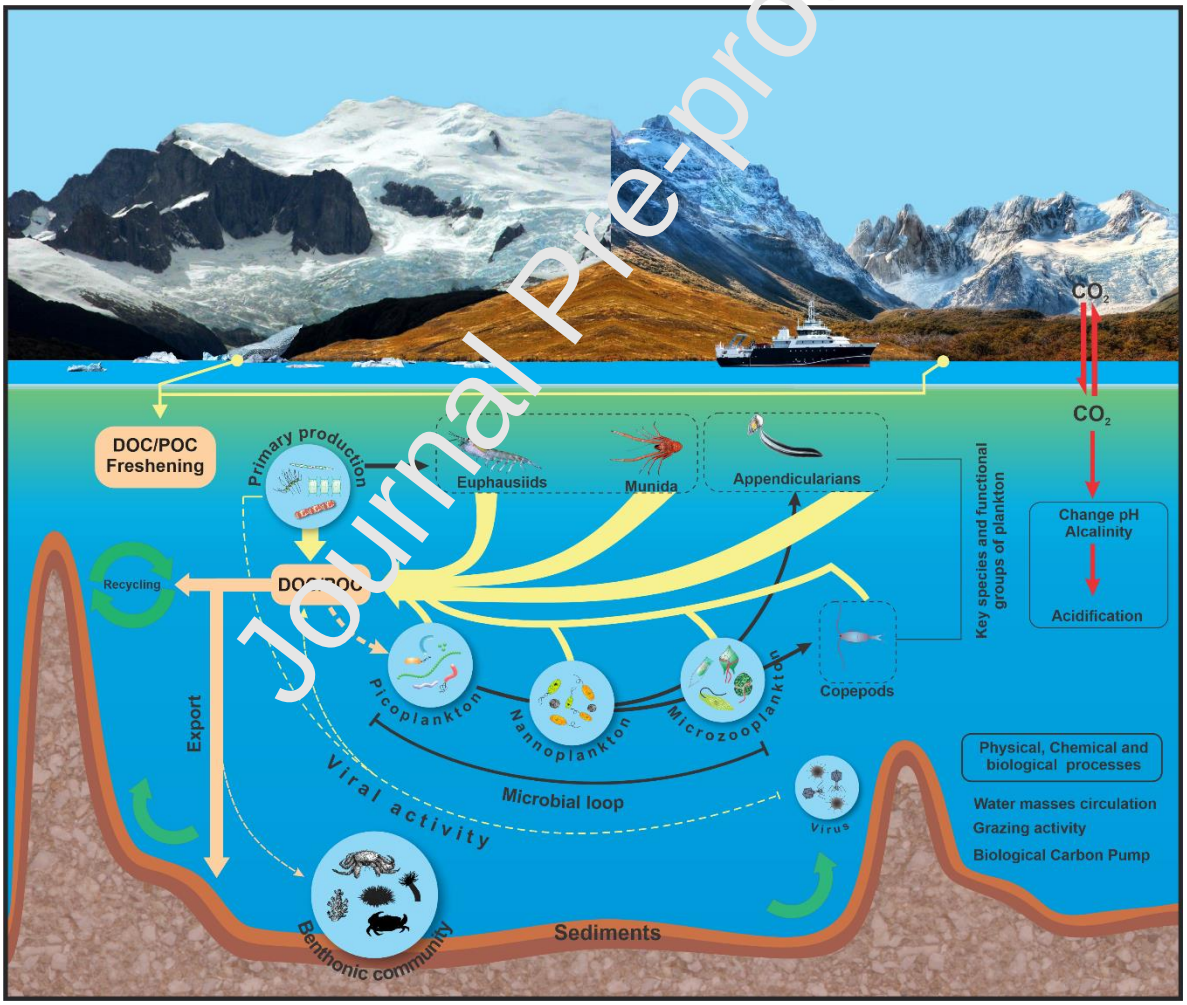

Figure 1: Summary schematic of the main physical, chemical and biological characteristics and associated processes along the Beagle Channel, where the local bathymetry (i.e., sills) affect the water circulation and residence time within/between

basins. Input of particulate/dissolved, organic/inorganic matter from terrestrial origin occurs mainly from glacial and vegetation fields at the western and eastern part of the BC, respectively. An active ocean-atmosphere exchange of CO_2 characterizes the area, along with an extensive vertical flux of particulates. The local food webs (classical and microbial), seem to be run by key species of euphausiids, squat lobster and appendicularians.

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Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: