



# Natural and Human Influences on Marine Processes in Patagonian Subantarctic Coastal Waters

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Some of the largest climate changes on Earth are projected for high-latitude polar and subpolar environments in the coming decades (IPCC, 2014). A number of simultaneous socio-environmental perturbations are affecting Patagonia (41–55°S), a vast and complex ecosystem whose economic and societal well-being depends on coastal resources (~80% of people live near-shore; the coastal economy provides >40,000 jobs). In this new scenario, overlapping natural variability (interannual – seasonal dynamics) and human-induced environmental changes (global change) are major drivers influencing the marine food web structure and functions. Evidence of large environmental changes has been detected in the Patagonia marine system through **(a)** regional-scale, climatic-oceanographic coupled anomalous events, **(b)** interannual hydrological changes (decreasing pattern) in freshwater river inputs (watersheds into fjords), and **(c)** more frequent coastal and oceanic microbial outbreaks (Harmful Algal Blooms). Those changes have highly uncertain effects for the basic functionalities, structure, and feedback responses of coastal systems and their coupling with hydrological (e.g., river streamflow) or biogeochemical (e.g., biological carbon pump) processes. The northern Patagonian fjords system is hypothesized to act as an indicator of large-scale climate change given strong environmental variability. This, combined with regional climatic-oceanographic events (e.g., El Niño Southern Oscillation, Southern Annular Mode) and effects of local anthropogenic activities (e.g., nutrient fluxes from extensive aquaculture, land change due to forestry) may impact the chemical and physical properties of the surface water, destabilizing biological productivity and chemical coastal processes. The present synthesis, which gives the results of systemic-sensitive chemical and biological variables, may be useful to managers and in preventing socio-environmental impacts from increasing natural and anthropogenic phenomena in Chile's southern coastal system.

**Keywords:** Patagonian fjords system, marine biogeochemistry, environmental – harmful algae coupling, ecosystem functions – stressors, salinity-driven system

## INTRODUCTION

The expansive Chilean Patagonia comprises a variety of marine and terrestrial forms: e.g., glaciers, the North and South Ice Fields, channels, bays, fjords, islands, lagoons, lakes, and straits. These create highly heterogeneous habitats for both native species and those (farmed and wild) introduced by aquaculture and agriculture. The terrestrial ecosystem is dominated by extensive mountain basins rich in native forests, rivers, pristine, and ultraoligotrophic lakes. However, the land has also been modified by historical colonization (human settlements led to changes in land use and forestation) and geological disturbances (e.g., volcanism, thermal vents). The topography of the Chilean Patagonia is irregular: steep mountain slopes (>1000 m above sea level) surround the fjords, penetrate the estuarine/marine system to depths ranging from 200 to 1000 m, and determine the importance of the forest – fjord interaction. Both terrestrial and aquatic ecosystems have high species richness, with birds, amphibians, and marine vertebrates and invertebrates, including several recently described cold-water hydrocoral species growing on vertical walls submerged at depths of 20 to 200 m (Häussermann and Försterra, 2007). Moreover, evidence of active geological processes (e.g., surface hydrothermal vents; Försterra et al., 2014) in Comau Fjord is relevant ecologically and biogeochemically (high methane and sulfide-enriched water), as these processes support trophic webs sustained by giant methanogenic bacteria (chemosynthetic communities) and diverse benthic species (Muñoz et al., 2014; Quiroga et al., 2016). Although the number of cold seeps in the fjord system remains unknown, patches of microbial mats, which obtain energy from the reduction of nitrate and sulfate, may play a key role in supporting a trophic link to invertebrate grazers (chitons, gastropods, mussels, and cold-water scleractinian corals) (Ugalde et al., 2013; Muñoz et al., 2014).

The oceanographic characteristics of southern Chile's coastal marine system are heavily influenced by freshwater that precipitates (up to 7000 mm per year) directly over the water surface and enters through the mouths of tributary rivers (Dávila et al., 2002). Southern Chilean Patagonia (41 – 50°S) is characterized by a few large rivers (Petrohue: 41°S; Puelo: 41°S; Yelcho: 43°S; Palena: 43°S; Baker: 47°S; and Serrano: 48°S), numerous small river basins, many glaciers and icefields (i.e., South and North Icefields). In this vast region, high freshwater discharges (2470 – 3344 m<sup>3</sup> s<sup>-1</sup>) into the eastern South Pacific Ocean are mainly observed between 42 and 50°S (Dávila et al., 2002). In these systems, high freshwater inflows (precipitation, glacier melting) generate strong vertical and horizontal density gradients, modulated mainly by a vertical salinity structure that determines a strong, permanent surface stratification – usually into two layers in coastal systems – of the water column (e.g., buoyancy frequency values of 20–60 × 10<sup>-3</sup> s<sup>-2</sup>; Valle-Levinson et al., 2007; Castillo et al., 2016). Although the magnitude of fresh water flowing into the ocean varies along the South Pacific Ocean, the large spatial effect of lower salinity (33.0 – 33.8) along the oceanic margin of the Patagonian sector of the Pacific Ocean (Acha et al., 2004) could play a role in the modulation of

physical (haline stratification), chemical (nutrient ratio: N:P:Si), and biological processes (primary production). On the other hand, the inner fjord region system that is influenced by heavy freshwater riverine and glacier-melt inflows is characterized by: (i) limited inorganic nutrient exchanges between the surface and deep layers of the water column due to haline stratification: tributaries contribute high concentrations of dissolved silicic acid (15 – 100 μM) to the surface layer, whereas Subantarctic waters deliver high concentrations of orthophosphate (1 – 2 μM) and nitrate (5 – 20 μM) to the deep layer, and (ii) both inorganic nutrients and radiation acting as the main seasonal limiting factors for seasonally high primary productivity (PP) (0.5 – 3 g C m<sup>-2</sup> d<sup>-1</sup>), which is dominated mainly by diatoms (90%) (Iriarte et al., 2007; González et al., 2013; Jacob et al., 2014).

This article reports the main features and achievements obtained over more than 10 years of interdisciplinary research carried out in the marine system of Patagonia using approaches such as synoptic oceanographic cruises, micro-mesoscom experiments, and time-series autonomous bouys. The paper unites the fields of oceanography, hydrology, and climatology as a means of improving our understanding of ongoing natural and human perturbations and their possible impacts on ecosystem services.

## RECENT THREADS IN PATAGONIAN MARINE SYSTEM

Should they come to bear, the potential impacts of human activities could certainly alter the structure and functioning of Patagonia's terrestrial and aquatic ecosystems (Table 1). These impacts may include the addition of nutrients (e.g., nitrogen) from agriculture and aquaculture, the removal of inorganic (e.g., silicic acid) or organic (e.g., carbon sources) nutrients through dams, and global phenomena that may be remote (global warming), may occur on interannual (El Niño Southern Oscillation, ENSO; Southern Annular Mode, SAM) or decadal/centennial scales (volcanic eruptions), or may be climatic (increased radiation, wind stress reduction of West Wind Drift) (Garreaud, 2018; León-Muñoz et al., 2018).

The marine system of northern Patagonia (41 – 44°S) recently experienced a strong interannual change in chlorophyll-a dynamics. Specifically, in two consecutive years (2009 – 2010), the magnitude of spring blooms was lower (less than 2 mg Chlorophyll-a m<sup>-3</sup>). This shift was associated with the cooling of the ocean surface and heavily disrupted the mollusk larval supply, mainly in the Inner Sea of Chiloé, from 2010 to 2011 (Lara et al., 2016). These strong seasonal changes vary on an interannual scale and are probably forced by regional oceanographic-climate changes such as ENSO and SAM. Furthermore, recurrent harmful algal blooms (HABs) were observed in coastal and oceanic areas in 2016–2017. These coincided with remote phenomena (ENSO, SAM) that led to very dry conditions, higher than normal solar radiation reaching the surface, and high sea surface temperatures. Specifically, results showed that anomalies created by ENSO and SAM led to drought on land and oceanographic conditions that set the stage for an

**TABLE 1 |** Main properties (ecosystem scale) that may be supported by the principal climatic, hydrological, and oceanographic features considering current and future scenarios of uncertainty in the Patagonian marine ecosystem.

Ecosystem property	Environmental features	Uncertainty results
Water reserve and river streamflow	<ul style="list-style-type: none"> <li>- Inner seas have cold surface waters enriched in silicic acid (up to 100 <math>\mu\text{M}</math>)</li> <li>- Estuarine circulation is two-layered in the upper surface water column</li> <li>- High variability of turnover times in microbasins of the inner seas</li> </ul>	<ul style="list-style-type: none"> <li>- Reduced precipitation due to global warming, with lower freshwater river inputs leading to fjords dominated by oceanic water sources, reducing water turnover time in microbasins (León-Muñoz et al., 2013)</li> </ul>
Nutrient availability and recycling	<ul style="list-style-type: none"> <li>- River freshwater is rich in silicic acid and overlays nutrient-rich (nitrogen/phosphorus) oceanic water</li> <li>- Terrestrial-aquatic systems are coupled through Patagonian forests and terrigenous sources (nitrogen, dissolved organic carbon) and geological features (e.g., silicic acid, calcium carbonate)</li> </ul>	<ul style="list-style-type: none"> <li>- Reduced/rising freshwater inputs will change stoichiometry ratios (N:P:Si) of inner sea areas</li> <li>- Changes in flux of micro- and macronutrients and DOC in the photic zone will affect the surface water biogeochemistry</li> </ul>
Biodiversity regulation and habitat refugia	<ul style="list-style-type: none"> <li>- Carbonate system of pH (7.5 – 8.0), <math>p\text{CO}_2</math> (250 – 1500 <math>\mu\text{atm}</math>), and aragonite has marked seasonal dynamic</li> <li>- Shallow cold seep sites have a reduced carbon-nitrogen system; microbial mats produce sulfur - methane used by symbionts</li> <li>- Surface cold waters octocorals are sensitive to pH</li> </ul>	<ul style="list-style-type: none"> <li>- Freshwater can reduce aragonite (undersaturation)</li> <li>- Winter advection of <math>\text{CO}_2</math>-rich waters can reduce aragonite</li> <li>- Rising biological respiration will increase <math>p\text{CO}_2</math>, reducing aragonite</li> <li>- Volcanic eruptions increase ash inputs, affecting pH and alkalinity of coastal surface waters</li> </ul>
Carbon energy as primary production	<ul style="list-style-type: none"> <li>- Marked seasonal fluctuations in surface waters: in spring-summer, a <math>\text{CO}_2</math> sink (high photosynthesis: 317–358 <math>\mu\text{mol kg}^{-1}</math>) and in winter, biological respiration processes and the upwelling of <math>\text{CO}_2</math>-rich deep waters are dominant (181–304 <math>\mu\text{mol kg}^{-1}</math>)</li> <li>- Abrupt winter-spring estimates of carbon budget through the food web: high carbon flux out of the photic zone in spring, fueling pelagic-benthic coupling (González et al., 2010)</li> <li>- Allochthonous carbon sources (DOM) for microbial utilization (Olsen et al., 2017)</li> </ul>	<ul style="list-style-type: none"> <li>- Interannual variability of phytoplankton dynamics: lower phytoplankton bloom biomass in spring will affect larval supply and mollusk growth rates</li> <li>- Changes in plankton functional groups (from diatoms to flagellates) will decrease carbon flux out of the photic layer, creating a less efficient food web</li> </ul>
Climatic processes	<ul style="list-style-type: none"> <li>- Remote events (ENSO, SAM) modulate hydrological-oceanographic processes</li> <li>- Zonal waterlines winds and radiation are main drivers of oceanic system (Garreaud, 2018)</li> </ul>	<ul style="list-style-type: none"> <li>- Climatic – oceanographic anomalies in summer will affect oceanic stratification, with recurrent harmful algal blooms (HABs)</li> </ul>

unusual “super bloom” of *Pseudochattonella* sp. (León-Muñoz et al., 2018). Due to global climate change, marine phytoplankton in the southernmost fjords region will likely experience increasing temperatures, constant glacial melting, and probably increased nitrogen (e.g., zooplankton excretion rates) in the future. We expect the interactive effects of these processes to heighten both the growth rates and toxicity of harmful algal species. Several of the toxic algal species favored by these environmental features – including *Pseudochattonella* spp. (dictyophytes), *Alexandrium* spp. and *Karenia* spp. (dinoflagellates), and *Pseudo-nitzschia* spp. (diatoms) – have been observed in the inshore and oceanic waters off Patagonia during the summer months of 2016 – 2017.

The oceanographic characteristics of the Patagonian fjord marine ecosystem favor the cultivation of aquatic species, explaining why more than 90% of aquaculture biomass (salmon, blue mussels, and macroalgae) are found in the inner seas of Patagonia. Optimal ranges of key variables (e.g., temperature, salinity, and dissolved oxygen) for the smoltification, growth, and physiological processes of fish and invertebrates, together with highly transparent river waters and the importance of physical

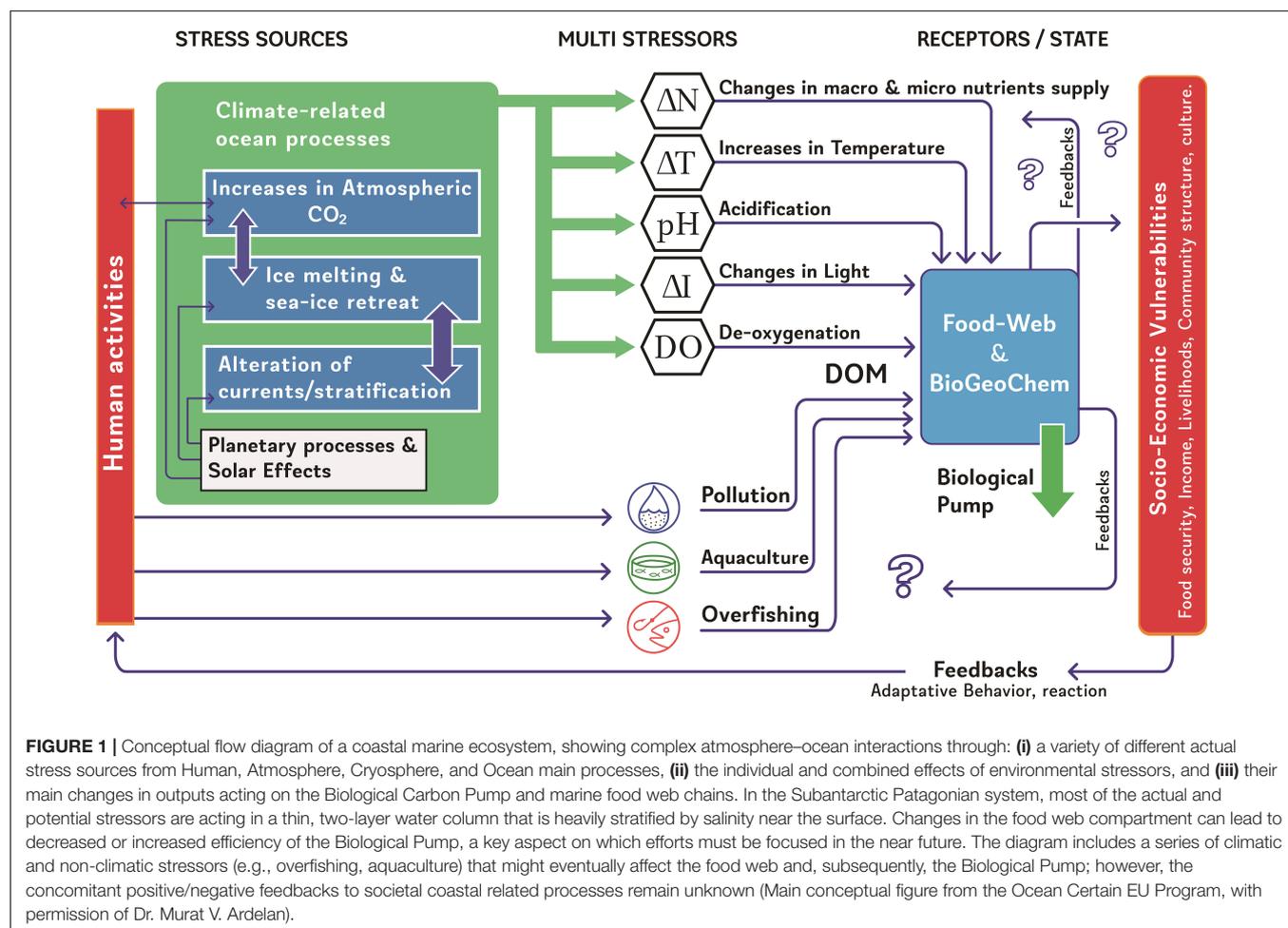
forcings (e.g., tidal currents as a process of particle dispersion) make these systems ideal for the development of aquaculture. In this scenario, aquaculture “uses” the surface layer of the sea (~25 m deep) for farming organisms, utilizing a variety of feeding strategies (pellets for salmon, natural phytoplankton for mytilids). However, the surface layer is precisely where the greatest physical (thermocline, pycnocline, mixed layer, and photic layer), chemical (halocline, nutricline, and oxycline), and biological gradients (biomass, primary production, and oxygen consumption) occur, making this thin oceanic layer highly vulnerable to external disturbances. Specifically, the addition and removal of inorganic and organic substances at the surface from anthropogenic activities (e.g., aquaculture, agriculture, forestry, and hydroelectricity) could represent, in the near future, a new critical state for the Patagonian marine system. For example, the stoichiometric ratio for three inorganic nutrients (nitrogen:phosphorus:silica, 16:1:1) in the fjord surface layer is expected to deviate under three environmental regimes: (i) lower flow from large Patagonian rivers (freshwater enriched in silicic acid) (León-Muñoz et al., 2013), (ii) frequent advection of deep

oceanic waters with high orthophosphate, nitrogen, and CO<sub>2</sub> levels (Torres et al., 2014), and (iii) the addition of nitrogen (ammonia) through the excrement of fish and mollusks farmed in the coastal waters off Patagonia (Soto and Norambuena, 2004).

Results from recent microcosm experiments performed in the Patagonian fjords and considering scenarios of ammonium addition by aquaculture (Olsen et al., 2014, 2017) have indicated that this nitrogen compound is highly “bioavailable” in the surface layer, mainly for biological assimilation processes by phytoplankton and bacteria. One of the main ecological implications of these mesocosm results is the possibility that an excessive increase in surface ammonium concentrations (ammonium flux higher than 1  $\mu\text{mol N L}^{-1} \text{d}^{-1}$ ) could, in the near future, trigger rapid and sustained growth of the autotrophic biomass, associated with increased bacterial production rates (i.e., higher respiration rates and seawater  $p\text{CO}_2$ ). This would eventually lead to sporadic, low-oxygen events in the photic layer, which would have negative consequences at higher trophic levels (fish and mollusk mortality). Finally, an important change in the components of the food web due to frequent pulses of nutrients (e.g., ammonium, silicic acid) or dissolved matter (e.g., dissolved carbon substances)

from external sources could modify the trophic state of the ecosystem, shifting it from predominantly autotrophic (diatoms) to predominantly heterotrophic (flagellates) (Thingstad et al., 2010).

Recently, studies of northern Patagonian fjords influenced by rivers have shown strong changes in the seasonal dynamics of the carbonate system variables in the surface layer. High-frequency pH/ $p\text{CO}_2$  measurements taken during a seasonal cycle in a northern fjord showed that riverine freshwater inputs and phytoplankton productivity affected the chemistry of the fjord, enhancing the shift from CO<sub>2</sub> sink in summer–autumn (high primary production) to CO<sub>2</sub> source in winter (high community respiration, CO<sub>2</sub>-rich oceanic water advection). Given the high PP of the northern Patagonian fjords in spring–summer, with strong seasonality in the air–sea carbon flow, the dynamics of the carbonate system indicate that the atmospheric–oceanic CO<sub>2</sub> exchange creates a CO<sub>2</sub> sink system in the far southern fjords under spring–summer conditions (Torres et al., 2011). However, seasonal  $p\text{CO}_2$  flux data showed that a river-influenced northern fjord (Reloncavi fjord) was a strong CO<sub>2</sub> sink in the austral spring–summer and a CO<sub>2</sub> source in winter, resulting in an annual net efflux (0.71 mol CO<sub>2</sub> m<sup>-2</sup> yr<sup>-1</sup>). This result seems to suggest that the net uptake of CO<sub>2</sub> by phytoplankton



in spring–summer is offset by heterotrophic respiration in winter. The high PP in the coastal waters off Patagonia creates an efficient flow of matter (carbon) and energy through higher trophic levels such as zooplankton (Patagonian krill), mollusks (bivalves), cold water corals, pelagic fish (sardines), and whales.

The Subantarctic water chemistry in the top 50 m of the inner seas of Patagonia varies markedly by season (spring–winter) in terms of pH, alkalinity, and concentrations of aragonite, as well as nutrient ratios (N:P:Si). Specifically, aragonite is an indicator of the saturation level of the form of  $\text{CaCO}_3$  in seawater available for use by the mollusk larvae that require  $\text{CaCO}_3$  for shell formation. In winter, the state of  $\text{CaCO}_3$  saturation in Patagonian surface waters is close to undersaturated for calcium carbonate in the form of aragonite ( $\Omega < 1$ ) (Torres et al., 2011; Alarcón et al., 2015), suggesting that increased freshening and acidification may undersaturate surface waters in the short term. Furthermore, an alteration in the winter–spring dynamics of aragonite saturation would have implications for the survival of larval stages of benthic shelled mollusks. For example, a delay in undersaturated aragonite values ( $\Omega < 1$ ) toward the spring months could negatively affect survival of early stage mollusk larvae during this period, ultimately affecting their growth rates (Ekstrom et al., 2015).

A different pattern can be expected in the southernmost region, particularly the Subantarctic Magellan ecosystem (50–55°S), where most glacier tongues (e.g., Marinelli, Ventisquero, and Santa Inés) have experienced some degree of retreat (Bown et al., 2014) as well as increased ice melting processes and higher volume inputs of freshwater to the fjord system. Whatever their causes (atmospheric warming, less precipitation, and Calvin cycle), these effects are expected to continue along with important atmosphere–ocean interactions that may profoundly influence biological processes in marine fjords. In general, when freshwater enters a fjord, it creates a “front”; this low-salinity layer provides vertical stability (deepening the mixed layer) and nutrient-enriched surface waters. Surface waters within the Strait of Magellan system are mainly derived from mixing between oceanic Subantarctic Surface Water (SAAW) and nitrate-poor, continental freshwater (Modified Subantarctic Water; Sievers and Silva, 2008; Torres et al., 2014). Here, the main phytoplankton blooms occur in spring–summer along the coast, when relatively high rates of primary production ( $1 \text{ mg C m}^{-2} \text{ d}^{-1}$ ) may be supported by the shallowing of the mixed and euphotic layers, high near-surface light levels, and abundant macro- and micronutrients (Iriarte et al., 2001; Lutz et al., 2016). Given ongoing global changes and their direct effect on glaciers, it remains difficult to predict how high freshwater fluxes and strong stratification will impact glacial–fjord systems, especially in terms of the efficiency of the biological carbon pump (Figure 1).

Some recent volcanic eruptions (Chaiten in 2008, Puyehue-Cordón Caulle in 2011, and Calbuco in 2015) could have temporarily impacted both terrestrial and aquatic habitats and, therefore, the structure and functioning of the biotic (including human) communities that inhabit and use the coastal area of

far southern Chile. Specifically, the precipitation of volcanic ash (rich in silica and Fe; Torres et al., 2014; Browning et al., 2015) into the system of basins and tributary rivers flowing into estuarine/marine fjord systems altered several aspects of the water chemistry: suspended material content (mainly dissolved inorganic, organic carbon and particulate carbon), light penetration through the short photic layer, and the properties of the carbonate system (pH, alkalinity). For example, after the eruption of the Calbuco volcano (May, 2015), pH dropped to 7.2 in the first 4 m of depth, returning to normal (7.8) after 10 days (Vergara et al., 2016). One major biogeochemical implication was the capacity of the marine system for resilience – mainly when facing changes in pH – due to its great buffering potential. On the other hand, trends (e.g., lower freshwater flows) observed on some rivers in northern Patagonia (Río Puelo; León-Muñoz et al., 2013) and strong river–fjord–ocean interactions could have complex biogeochemical implications due mainly to changes in alkalinity, oxygen concentrations, and dissolved matter in coastal and marine environments.

## CONCLUSION

At present, Chile’s southern Patagonia region is experiencing unprecedented environmental impacts from climate change (e.g., warming, ice melting, and glacial retreat), such that aquatic organisms (including humans) are expected to *respond* and *adapt* in their surroundings during the near future. Environmental changes will affect the basic functionality and feedback responses of coastal systems (Figure 1) as well as couplings with hydrological (e.g., river streamflow, glacier melting) and biogeochemical (e.g., carbonate system) processes. This initial qualitative analysis of some potential effects of disturbances – both natural and anthropogenic in origin – on Patagonia’s coastal marine system helps identify near-future mitigation actions and mechanisms. For example: Lowering nutrient loading in coastal waters would reduce hypoxia in the surface sediments and deep water column as well as the frequency of HABs. In turn, encouraging the farming or extraction of diverse new autochthonous fishes and invertebrates species (as opposed to the monospecific strategies that presently focus mostly on salmonid and mussel species) would reduce social vulnerability to environmental impacts. Finally, the availability of information to science through aquaculture-related industry-research partnerships, offshore systems that autonomously monitor new biogeochemical variables (pH, aragonite, ammonium), and longer time-series of the main variables (chlorophyll-a, sea surface temperature, dissolved oxygen) all serve to support interannual and seasonal variability of metabolic functions of marine species as well as continually verify the “health” of the system.

## AUTHOR CONTRIBUTIONS

JI conceived the idea, integrated the information, and wrote the paper.

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**Conflict of Interest Statement:** The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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