Natural and Social Sciences of Patagonia

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Global Change in Atlantic Coastal Patagonian Ecosystems

A Journey Through Time

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Natural and Social Sciences of Patagonia

Despite being an underpopulated region, Patagonia has attracted the attention of scientists since the very beginning of its settlement. From classical explorers such as Darwin or D'Orbigny, to modern science including nuclear and satellite developments, several disciplines have focused their efforts on unraveling Patagonia's natural and social history. Today, scientific and technological research is shifting from being shaped by northern agendas, towards more locally oriented objectives, such as the management of natural resources, the modernization of energy production and distribution, and the coexistence of rural and cosmopolitan social lifestyles. At the intersection of all these topics, new conflicts concerning the economy, human development, population, and the proper and long-standing planification and management of the landscape and its natural resources have emerged. These conflicts, of course, have also caught the attention of many interdisciplinary research groups.

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Foreword: What Is This Book About?

This book is about the past, present, and future of the environment and environmental changes in the southwestern Atlantic Argentinean Patagonian coast; a beautiful and always windy region. The book is truly a journey through time, describing the environmental and biotic changes and, at the end, including humans as a main component challenging the environmental sustainability. The content will be appealing to scientists interested in environmental change, but it should also be of interest to managers, policy makers, and planners. The chapters focus on different components of the ecosystem and different time scales, and include the most recent research in climate and oceanographic science, ecology, urbanization, management, and conservation in coastal Patagonia. Finally, the authors also provide insights and strategies to develop a human-environment coexistence in a changing "near future" scenario. As the reader will see, the Argentinean Patagonian coast is also a land of science, conservation, and new urban developments.

The Argentine Patagonian coast extends for around 2000 km (it depends on how small or large is the unit of measure used) from the South of the Argentina Pampas (about 40°S) to the southern tip of South America (58°S). It is a relatively sparsely inhabited coastline (about one million inhabitants) with a few relatively larger cities with no more than a few hundred thousand people each (see chapter by Capandeguy and Sprechmann). Most of the coastal Patagonia is characterized by the presence of sharp perpendicular cliffs, which may be up to 70 m high, indicating an erosive coastal environment (see chapter by Isla and Isla). Overall, as seen in the chapter by Pessacg et al., Patagonia is a dry and windy region. Including its coasts and offshore marine shelves, it is dominated by the famous Westerlies, winds that flow from subtropical high-pressure belts to subpolar/circumpolar low-pressure belts. These winds are present year around, with a maximum intensity between 45° and 55° S. But, interestingly, during the warm seasons, wind patterns in the coastal areas are strongly influenced by the "sea breeze." This is the result of differential air heating over coastal land and the adjacent waters, and thus occurs mostly during the afternoon in the spring and summer months when the heating difference is higher. Coastal Patagonian "sea breeze" is still a poorly studied phenomenon, but is well known and highly predictable by the local population. This is good for windsurf and kiteboarding, but it also has the potential of being useful for benthic intertidal or shallow subtidal species. Indeed, the high predictability of this phenomenon generates a strong potential for selection, and thus intertidal and shallow subtidal sedentary benthic species may use the current generated by this wind (surface flows onshore during the day, while bottom water flows offshore) to export or import their planktonic larvae. The well-known phototaxis of many of these larvae appears to have arisen to take advantage of this transport mechanism.

Thereby, the coast generates a typical boundary ecosystem, with biota specifically adapted and a mixture of species from the two adjacent environments linked by energy, material, and organism flows across this boundary. The coastal Patagonian marine biota is not homogeneous (see chapters by López-Gappa, and Horta et al.). To the north of 43°S–44°S, there is the warm-temperate waters of the Argentine Biogeographic province (that can extend up to southern Brazil), and to the south, there is the cold-temperate waters of the Magellanic Biogeographic province (that can extend up to southern Chile in the Pacific). In the adjacent land, the central and coastal Patagonian climate is semi-desert (see chapter by Pessacg et al.) with low rainfall levels mainly concentrated in winter. Thermal amplitude is important, but compared to the same latitudes of the northern hemisphere, the thermal variations in Patagonia are much lower, which is largely the product of the oceanic environment. The coastal Patagonian vegetation, adapted to arid and windy environments, is dominated by the shrub steppe of the Monte Biogeographic province in the North (approximately up to 43°S) and the grass steppe of the Patagonia province in the South. Thus, the interface is not homogeneous given the combination of different terrestrial and marine biogeographic provinces. Moreover, while the coastal land is desertic, the coastal waters are immersed in one of the large world "oceanic oases," the Patagonian shelf. This region belongs to one of the large marine ecosystems (LMEs), which are regional units described for the conservation and management of living marine resources. In this case, this LME incorporates the coastal environments, continental shelf, slope, and ocean basins, covering 6,581,500 km^2 of marine platform. Why this area is one of the highly productive shelves of the World is described and discussed in the chapter by Saraceno et al. But essentially, besides being fueled by the cold, nutrient-rich waters coming from the Antarctic Circumpolar Current either through the Malvinas Current (offshore along the Patagonian slope) or through the Patagonian Current on the shelf directly affecting the coast, a series of upwellings ("marine frontal systems") enhance the productivity of this area. The authors also describe in detail the different types of coastal features (e.g., gulfs, shelves) that regionally affect the oceanography and the productivity of this region.

This marine high productivity leads to large local biodiversity (see chapters by López-Gappa, Galván et al., Crespo, Horta et al. and Quintana et al.) The area is also of importance for distant migratory birds, fish, turtles, and marine mammals, including some of the most charismatic species that breed and feed in this region (e.g., black-browed albatrosses, Magellanic penguins, southern elephant seal, and southern right whale). The Patagonian sea, as expected, supports several high-volume fisheries, primarily for Argentine hake, Argentine red shrimp, and Argentine shortfin squid. Obviously, there are conflicts between fishing and wildlife, which is discussed further in the chapters by Crespo, Narvarte et al., and Sala.

The coastal geography is characterized by tall sharp cliffs that generate beautiful scenic sites. They are made up of layers of sedimentary rock and are sometimes loaded with fossils, mainly invertebrates such as bivalves. These cliffs tell a story of large environmental changes. Indeed, as described in the chapter by Griffin et al., the presence of fossils in these mainly Cenozoic rocks as indicators of changes has been known for many years, although the scientific interest started with the first scientific explorers, such as d'Orbigny (1834–1847)[1] and Darwin (1846).[2] Now, this evidence tells us that since the initial opening of the Atlantic Ocean in the Early Cretaceous, this region has been affected by a number of marine transgressions. Undoubtedly, the separation from the Antarctic generating the Antarctic Circumpolar Current became a turning point in the provincialization of the weather in Patagonia. The fossil record also reflects large climatic oscillations and large changes in the sea water level, with important retractions and intrusions of the sea on the current Patagonian land. However, a trend towards desertification has been a constant process, although in the Late Pleistocene-Early Holocene transition when humans arrived in Patagonia, the climate was drier and colder than at present.

Closer in time, during the quaternary, dynamic processes affected the Patagonian coasts, leading to the characteristics of the beaches that we have today, which are described in the chapter by Isla and Isla. The combination between sea level change with alterations in the fluvial discharge intensity due to climatic variations models the coastline. Indeed, the estuaries and deltas have changed notoriously during the Holocene. Just due to changes in the watershed, some rivers increased their discharges where others reduced their flow depending on the dynamics of the glaciation, leading to estuaries of different shape and size that we have today.

Nowadays, there is no doubt that the Earth is enduring climate change, with a strong warming of the planet, accelerated at an unusually high rate due to anthropic effects. Although the phenomenon is directional (increase in global temperature), the effects vary widely between regions. Most likely, due to the oceanic characteristics, the effects of climate change are less important on the Patagonian coast when compared with the northern hemisphere. A well-known feature of global warming scenarios is that there is stronger warming on the land when compared with the sea. In the northern hemisphere, a region with a high land-sea ratio, the annual average temperature is higher than the southern hemisphere, and the northern hemisphere has been warming faster than the southern hemisphere since the early 1980s. Here, in the chapter by Pessacg et al., the authors describe the current climate characteristics and assess expected climate changes in Patagonia with a special emphasis on coastal areas. They show that mean temperature has been increasing in the continental Patagonia, at least during the last 70 years, but this warming trend is not

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[1] d'Orbigny A (1834–1847) Voyage dans l' Amerique meridionale.

[2] Darwin CR (1846). Geological observations on South America. Being the third part of the geology of the voyage of the Beagle, under the command of Capt. Fitzroy, R.N. during the years 1832 to 1836. 337 pag. London: Smith Elder and Co.

occurring in the coastal areas where there is even evidence of cooling. Precipitations show a large interannual variability; although it seems to be a decreasing trend, extreme events are predicted. Overall, projections indicate that temperature and precipitation will increase. On the coastal waters, the chapter by Saraceno et al. explored the possibility of having detectable changes in oceanographic variables. Overall, they found that water temperature in the Argentine shelf shows some increase in surface in the northern part of the Patagonian coast, while the southern end of this area is cooling. There is also some increase in primary production in certain areas. Additionally, an increase in sea level occurs as expected for the southwestern Atlantic (approximately 1.6 mm year^{-1}), with some areas where the increase is higher (part of the San Matías gulf). Indeed, the coastal Patagonian sharp cliffs are evidence of an actual erosive environment (see chapter by Isla and Isla), with an estimated cliff retreat that varies between 0.3 and 1.4 m year^{-1}. In the chapter by Saraceno et al., the authors analyze possible effects on circulation based on models and discuss the potential oceanographic effects of increased freshwater input in the southern part of the Patagonian region due to the melting of the glaciers. Overall, changes are not important but are already occurring.

However, although the effects may still not be too apparent, we know that the inertia in the climate system may lead to effects in the future. Even if there is a complete stop to carbon dioxide emissions, the temperatures, and thus sea level, will continue increasing for several centuries. As described before, although still not very important in magnitude, the Patagonian coast is already enduring changes. Moreover, the coastal human population and urbanization has increased, generating an increase in industries, agriculture activities and therefore having some effects. These changes are expected to affect primary production, which in a highly productive region may result in important environmental changes. In the chapter by Villafañe et al., the authors extensively describe the complexity of understanding the final effects of different environmental drivers on the plankton dynamics. In particular, they do an exhaustive analysis of regional studies addressing the relationship between environmental change drivers and plankton abundance and diversity, discussing the methodological aspects and their limitations for these studies. Most of the studies performed have evaluated the individual responses to solar ultraviolet radiation (UVR), and a few evaluated the spatial distribution of zooplankton in relation to anthropogenic influence. They note that there is a gap in studies on pollutants such as heavy metals and microplastics, specifically experimental ones. There is no doubt that the studies done so far have contributed significantly to our understanding of the effects. However, the authors suggest that there is a need to integrate different trophic levels in order to best understand plankton responses and improve predictions of the impact of global change in this region.

There is no doubt that the interaction between species adds an extra complexity to understand the effect of drivers of climate change on the biotic system. As discussed in the chapter by Valiñas et al., the effects of environmental changes on the species are complex and not straightforward given that changes in the environmental conditions can modify the outcome of species interactions leading to different community structures. Hence, making predictions on the direct effects of global change on individual species or groups of species may not be the best approach. To support their assertion, the authors of this chapter review the information about how some global changes related to environmental changes (e.g., increase in nutrient inputs, changes in UVR) affect biological interactions of species inhabiting coastal Patagonia. In particular, they review two well-known common regional environments, the coastal vegetated areas (salt marshes and macroalgal beds) and the near-shore waters. The evidence shows that the biological outcome of environmental changes is hard to predict if it is not investigated in the context of community structuring processes.

Even though community dynamics are well known and the species interactions well understood, the arrival of a new species may completely change the species relationships and thus community structure. This is exactly what happens with species invasions, which is, without a doubt, an anthropogenic effect that causes global change and has become one of the most serious threats to the World's coastal ecosystems. The Patagonian coast is not an exception. While Valiñas et al. show examples on how invasive species alter native communities through biological interactions, the chapters by López-Gappa and Horta et al., describe and analyze the invasion of non-indigenous benthic invertebrates and algae into intertidal and shallow subtidal habitats. There are a few introduced species, but the green or shore crab, the intertidal reef forming Japanese oyster, and the shallow subtidal brown wakame kelp are potentially the most important. The Japanese oyster was introduced to a bay in the northern limit of the Patagonian coast (San Blas bay) for aquaculture purposes in 1982, and fortunately, today their presence is mainly restricted there. The wakame kelp (see chapter by Horta et al.,) was first detected on the Patagonian coast in 1992 but now occupies more than 1000 km and continues to spread. Overall, their community effects are still poorly known, but all the species have the potential to spread along the whole Patagonian coast and generate important ecosystem impacts.

However, to actually understand the ecosystem effects of environmental change requires to know a reference baseline condition, which usually needs long-term information. Indeed, it will be desirable to have long-term ecological studies to get an integrated understanding of how the components of the ecosystems interact over time in a changing environment. Unfortunately, long term datasets are uncommon for many species, communities, or ecosystems, but count of population numbers and some life history characteristics are available in this region for some fish assemblages (see chapter by Galván et al.), which is available in greater detail for marine birds (see chapter by Quintana et al.) and marine mammals (see chapter by Crespo), allowing exploration of certain effects of a changing environment.

If the sea waters of coastal Patagonia are warming (see some examples in the chapter by Saraceno et al.), it is expected to have a southward range shift of warm-temperate species (those originated in the Argentine Biogeographic province), including fishes. In the chapter by Galván et al., the authors, by analyzing data of the coastal Patagonian fish assemblages since the 1970s, show evidence that this is starting to happen. They identify an increase in the number of fish species due to the arrival of warm water species in the northern and central Patagonia coasts.

Essentially, they see a pattern of tropicalization of temperate waters such as described in other parts of the World. Interestingly, several species, including elasmobranchs, have become less common, probably due to the direct or indirect effect of fishing. How these new arrivals affect the ecosystem functioning still remains to be investigated.

The Patagonian coasts are inhabited by several important bird species, including the three penguins, a petrel, five cormorants, three terns, and two skuas (see chapter by Quintana et al.). Many of these species have very large, colorful, and noisy colonies that constitute important touristic attractions, mainly during the breeding seasons. However, natural and human-induced environmental changes are their main threats. Climate variability largely influences their population dynamics, and thus they are good indicators of marine environmental changes. On the Patagonian coast, there is some long term (mainly population numbers) information on the Magellanic penguin, petrels, and the imperial cormorant. According to these data, one of the largest Magellanic penguin breeding colonies is declining, but new colonies are emerging elsewhere. On the contrary, petrels are increasing in their two breeding colonies. However, as described in the chapter by Quintana et al., just population numbers – the most common information – may not be sufficient to understand the actual or potential effects of climate change. To address this issue, they describe their results from a relatively long-term integrated dataset (i.e., 16-year period) for the imperial cormorant. Their information includes population numbers, breeding parameters, and foraging patterns (by sex and age), which allow them to describe inter-annual variation. At the same time, they examine how both sexes exploited the depth-dependent “energy landscape” of the area around the colony. Finally, in their chapter, Quintana et al. discuss the value of long-term tracking, breeding, and population data for ecological studies, as well as the implications for conservation and management strategies.

Although the effects of climate change on marine mammals in this region are not evident, they have endured large changes due to human activities. Fortunately, there are several species with long-term information. In his chapter, Crespo reviews the existing data of distribution, population numbers, and trend of the most conspicuous species of marine mammals in this region, which includes the South American sea lion, South American fur seal, southern right whale, and the dusky and Commerson’s dolphins. Several of them are recovering after being on the verge of extinction due to interactions with humans, mainly during the early European colonization. None of them has reached a stable population size. However, although it is unknown what will be the equilibrium size for these populations, the author emphasizes that in an expected changing environment, there is a need to seriously consider managing the ecosystem under a new paradigm, which includes fisheries. The Patagonian sea is highly productive, supporting large fisheries based primarily on Argentine hake, Argentine red shrimp, and Argentine shortfin squid (see chapter by Narvarte et al.). All of them are also connected directly or indirectly through the food web with all marine mammals (and also oceanic birds). Given that it is expected that these fisheries will continue operating, it will be necessary to manage the fisheries in order to coexist with a healthy population of top predators. However, given that some of these species are highly migratory, just an agreement restricted to the Argentine sea may not be enough. It should also include international management strategies.

As described before (see also chapter by Narvarte et al.), large-scale fisheries are important in Patagonian waters, which have significantly increased since last century, producing more than three quarters of the Argentine landings and exports. But, the relationship between environmental change and Patagonian fisheries is still poorly understood, perhaps because there is still no strong evidence of the effects of environmental changes. However, there is some strong evidence of humans inducing changes in fish and shellfish populations. In this book, Narvarte et al. tell us the history of the Argentine fisheries, and describe the few cases of strong effects on the fish population. As they describe, problems in Argentina's fisheries have been more related to overfishing than to environmental problems. Overfishing is one of the main anthropic stressors, but the effects of climate change constitute another stressor that, even if it is not acting now, is expected to be important in the future. Given that, in their chapter, Narvarte et al. develop an ad-hoc framework to examine the vulnerability of stocks of the Patagonian fisheries, taking into account the most evident physicochemical (temperature and acidification) and anthropic (overexploitation and market forces) stressors. Using this technique, they identify fisheries that are more vulnerable to different stressors, including the ones related to environmental changes. Moreover, the authors discuss alternatives to reduce vulnerabilities and discuss the management options under an ecosystem management approach. The take-out message is that well-managed fisheries are better prepared to confront environmental changes.

Going back to the coastline, there is no doubt that humans have long been attracted to the coastline, most likely due to the relatively easy access to resources. There is even evidence that early humans left Africa along the Red Sea coastline and colonized the Americas before the ice-free corridor opened up. Nowadays, about 40% of the human population live on the coastline. Human settlements on the Patagonian follow the same pattern. In their chapter, and as Gómez Otero and Svoboda report, the northern part of the Patagonian coast has been occupied since at least the Middle Holocene until the Natives-European contact period. These hunter-gatherers exploited marine resources such as mollusks, fish, birds, and pinnipeds. The large coastal shell middens, or "conchales", generated at least 5,300 years BP, indicate the heavy use of intertidal and or shallow subtidal as a food source. The relative importance of food items in the diet of humans varies over time; while mussels were more common at the beginning, Southern sea lions became more common by the end of this period. This change in the diet was probably due to changes in human behavior, which may have been influenced by climate change, changing their relationship with the coastal environment. Interestingly, the decrease in the representation of marine fauna in their diet is hypothesized to be linked to the introduction of horses, which have other needs and provide a lower hunting cost tool to capture terrestrial prey such as guanacos and rheas.

Today, the Patagonian human population is primarily associated with the coasts (see chapter by Capandeguy and Sprechmann), and urbanization is generating increasing pressure on coastal ecosystems. To provide ideas of how to confront this problem under a changing environmental scenario, the chapter by Capandeguy and Sprechmann gives a description of the recent history of urbanization in the region, analyzing the urban planning, and the coastal uses by tourism. Reviewing the literature, the authors analyze the different territorial perspectives based on different conceptual backgrounds (i.e., a land-sea strip with humans concentrated within a large territory, a mosaic of phenomenological landscape, and a captive environment within viscous hyperobjects), which were used to understand the coastal Patagonian urbanization. The principal historical features and main activities of cities and towns are described, detailing their major challenges and their social and environmental vulnerabilities. The strong relationship between urbanization and tourism, a major activity of several urban areas of the Patagonian coast since the mid-twentieth century, is also analyzed. They discuss urbanism and its adaptation in times of climate change. Perhaps, as the virus pandemic is teaching us, the Anthropocene, or the time where nature was dominated by humans, is coming to an end and we should review our relationship with nature. Thus, the paradigm discussed in the chapter by Capandeguy and Sprechmann, of achieving a “multi-species architecture and urbanism,” came at the right moment. Interestingly, this paradigm involves considering marine conservation as part of urban planning.

Besides local urbanization, human activity in general is a major threat to biodiversity. The human population is growing and is continuously moving up the “carrying capacity,” which threatens biodiversity because their higher use of resources directly (e.g., exploitation) or indirectly (e.g., displacing other species) affects biodiversity. Coastal Patagonia, an area with high biodiversity, is not an exception to this pattern. Although their human population size is rather low, their effects could be important. As Sala describes in his chapter, this is also a region with a variety of management actions aimed at regional or global conservation of species, habitats, and ecosystems. All fisheries are managed (see also chapter by Narvarte et al.), and there are several large-scale protected areas under different jurisdictional management. However, conservation science is a dynamic field of science, and Sala takes us through the development of the idea of conservation science up to the present, showing the many approaches to reach the goal of maintaining biodiversity. The author then provides us with the history of conservation science of coastal environments in Patagonia, noting the key role of stakeholder involvement, mainly through NGOs, in pushing many of these actions. However, such a wide range of management and conservation actions was not always developed under the same paradigm, which resulted in conflicts. Furthermore, in many cases, the view of the natural and social worlds as separate persists. Given that, he makes a strong point toward adopting the vision of a “social-ecological system” (SES), thus integrating the social and ecological dimensions in conservation science in general, and on the Patagonian coast in particular. This will undoubtedly be difficult due to the need to incorporate a multidisciplinary approach, but the results should be more robust and adaptive in a changing scenario. It is interesting to note that even coming from very different areas of science, the idea of adopting a “SES” view of development has similarities with the idea of developing with a “multi-species urbanism” approach proposed in the chapter by Capandeguy and Sprechmann. This convergence may be important when we think about the future.

In closing, this book takes us on a journey through time, mainly along the Patagonian coast, but also through the southwest Atlantic. On this trip we see the geological history, its environmental changes, its biodiversity, its first and current settlers, and its present and future problems derived from environmental changes. In the end, the authors propose a variety of ideas of how to converge to a vision of development based on sustainability, where, in a changing environment and even using their ecosystem services, we will be able to coexist in harmony with the different components of the ecosystem. That is why this book will not only be interesting for scientists but also for planners, managers, and decision makers.

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Introduction: When and How Our Journey Started

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Since its formation, our planet underwent significant alterations, from large displacement of land masses that resulted in the current continents and seas to an increasing oxygenation that changed the Earth's atmosphere. In addition, an intense volcanism activity released huge amounts of greenhouse gases (GHGs), mainly water vapor, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) into the atmosphere. The natural increase in GHGs triggered a key phenomenon, the "greenhouse effect", that allowed an increase of surface temperature making it possible the life on Earth (Tyndall 1863). For instance, the mean temperature of 15 °C at present would have been minus 18 °C without this effect (Mesarovic 2019). Paleoclimate investigations on ice cores allowed to infer the natural variations of one of the GHGs (i.e., CO_2) over geological timescales (~800,000 years; Fig. 1A, B), evidencing changes up/down over time as large as ca. 100 ppmv within time lapses of 10–30

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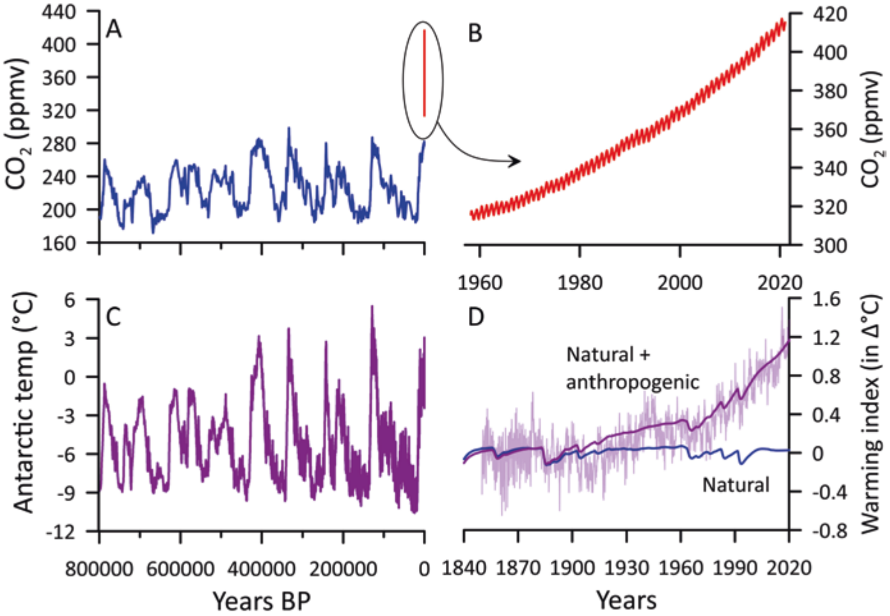

Fig. 1 Estimation of variations in carbon dioxide (CO_2) concentrations (**A**; Lüthi et al. 2008) and temperature (**C**; Jouzel et al. 2007) measured in Antarctic ice cores over the last 800,000 years before present. (**B**) Mean atmospheric CO_2 concentrations measured in the Mauna Loa Baseline Observatory since the 1950s (https://www.esrl.noaa.gov/gmd/ccgg/trends/). (**D**) The mean global warming index for the 1840–2020 period (https://www.globalwarmingindex.org/AWI/info_page.html; Haustein et al. 2017). The blue line represents the natural contribution (solar radiation and volcanic activity), the purple line shows the combined contribution (natural and human-induced) to the temperature change, and the evolution of the warming index over time

thousand years. These variations in CO_2 concentrations were accompanied with changes in temperature (Fig. 1C, D); hence, the Earth alternated between cold (e.g., the Little Ice Age, nineteenth century) and warm (e.g., Medieval Warm Period, 800–1300 AD) periods, such as demonstrated through paleoclimate investigations (Neukom et al. 2019). Fine measurements carried out by Keeling et al. (1976) on air samples taken at the Mauna Loa Observatory in Hawaii since the late 1950s showed that not only the increase of CO_2 in the atmosphere reached concentrations far above those due to natural variations (Fig. 1A, B) – as high as 420 ppmv in 2020 – but also that they increased at much higher rate, than previously observed, of about 100 ppmv in ca. 70 years. This higher rate of increase in CO_2 concentration over the last decades have been coupled with a concomitant increase of the global temperature of 1.2 °C in 120 years (Fig. 1D).

Some decades ago, researchers posed the possibility whether this "natural dynamism" observed in air samples and ice cores over short- and long-term timescales, respectively, could be influenced by humankind. This proposal lies in two important facts: (1) a huge increase in the human population occurred since the eighteenth century and (2) associated changes in the land, water, transportation, and energy use due to the increasing food demands and urban areas by growing population. The World's population today is 1860 times the size of that 12,000 years ago (i.e., ~4 million; Fig. 2A). A very low growth rate (~0.04% annually) prevailed from 10,000 BC to 1700, but since the industrial revolution, the human population expanded by 12-fold (Fig. 2A). This expansion in human population has triggered ca. 4-fold increase in the number of livestock heads (i.e., buffalo's, cattle, goat's, sheep's) since 1900 (inset Fig. 2A) and ca. 50-fold increase in the surface used to built-up areas (i.e., villages, cities, human infrastructure) since 1700 (inset Fig. 2B). Also, the increasing demand for aquatic food resources evidenced since the middle of the twentieth century has caused a sustained increase of fish landings and aquaculture production (Fig. 2C) as well as a more intensive presence of humans in the aquatic basins around the World (Small and Nicholls 2003). Finally, and as a consequence of the human expansion and domination on Earth, the motor vehicles and the energy use have increased by 6-fold, and the water use for domestic purposes by 4-fold since the 1950s (Steffen et al. 2020). This overexploitation of the natural resources and the intensive activities carried out by humankind have been translated into subsequent significant changes in our atmosphere and geosphere. In fact, other GHGs, in addition to CO_2, such as CH_4, N_2O, or SF_6, have recently drawn the attention of scientists and policy makers as they are steeply increasing over the last two–three decades (IPCC 2021). Some of these "minor" GHGs, in spite of their lower concentration than CO_2 in the atmosphere (between 100- and 1000-fold), have 25 (i.e., CH_4), ~300 (i.e., N_2O), and even ~23,000 (i.e., SF_6) times more global warming potential, and therefore, its uncontrolled increases into the atmosphere could accelerate (and accentuate) the ongoing global warming (IPCC 2021). Overall, and although it is considered that many natural drivers are responsible for the variations in the Earth's climate (especially in regard to changes in temperature), it is widely accepted that the increasing anthropogenic emissions of GHGs in the past decades are the major contributors (and responsible) of the large variations observed over the natural changes per se. These emissions are mainly derived from ruminants (2.3 ± 0.1 Gt CO_2 eq year^{-1}), natural gas, oils and industry (1.6 ± 0.3 Gt CO_2 eq year^{-1}), coal mining (1.2 ± 0.2 Gt CO_2 eq year^{-1}), rice agriculture (0.8 ± 0.7 Gt CO_2 eq year^{-1}), and burning biomass (~1.3 Gt CO_2 eq year^{-1}) (Montzka et al. 2011). They are also related with the rising rates of extreme climate phenomena (e.g., heat waves, storms, floods) that we are experiencing nowadays (Smale et al. 2019). These anthropogenic activities affect the Earth as a whole, and Steffen et al. (2004) included it into a more general concept commonly known as "global (climate) change" which was defined as *the profound alterations of the Earth's environment, due not only to the great forces of nature or extraterrestrial sources, but to the numbers and activities of people*.

The excess of GHGs (mainly CO_2) released to (and accumulated in) the atmosphere and the associated warming are subsequently modifying pivotal processes for Earth functioning, such as in the thermohaline circulation (Sandström 1908). This circulation can be resumed as a conveyor belt (Fig. 3) in which the hypersaline brine of high density originated at the poles (at the time of ice formation) flows out

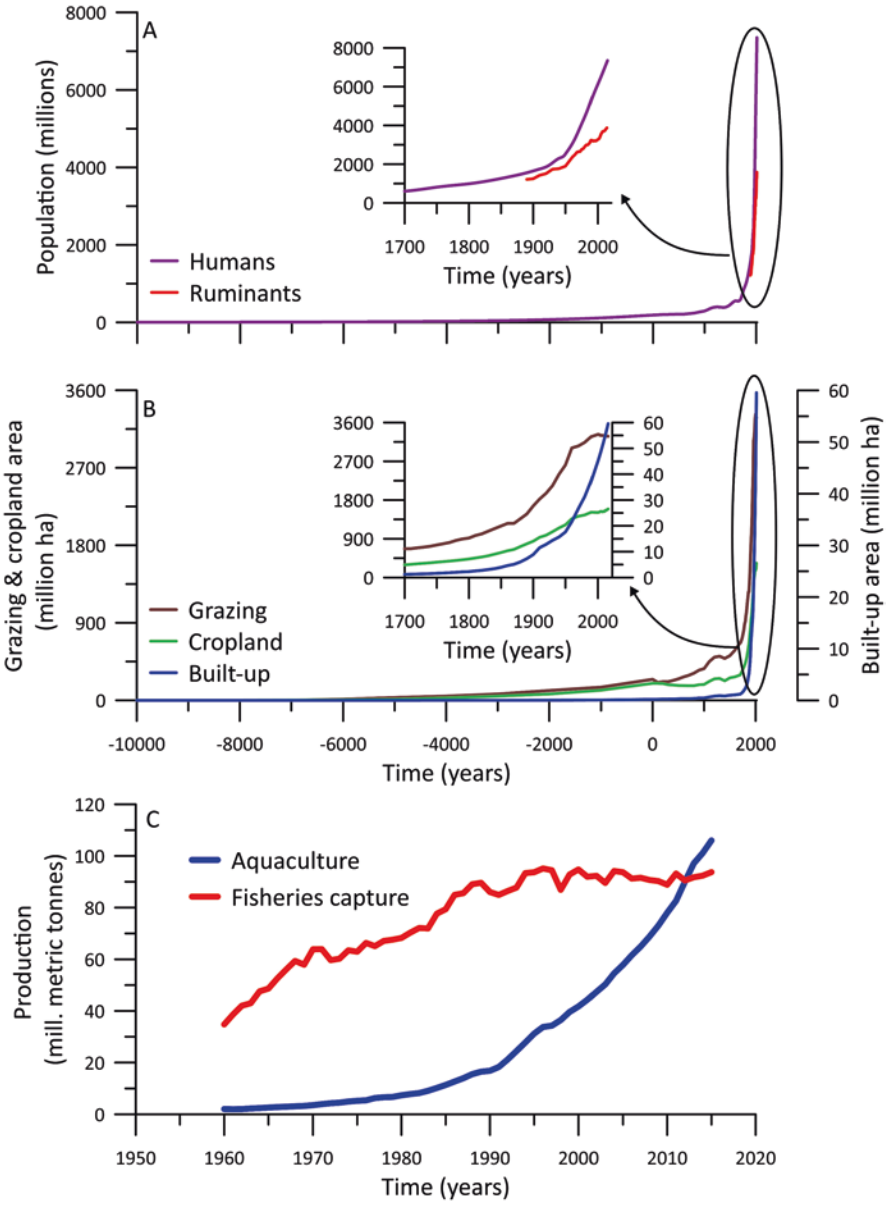

Fig. 2 Variations over time of population, the use of land and food production. (**A**) World population growth over the last 12,000 years and ruminants increase since the mid-nineteenth century and (**B**) the total land area used for grazing, cropland, and built-up (villages, cities, towns, and human infrastructure) over the last 12,000 years. Source: M. Roser, H. Ritchie, and E. Ortiz-Ospina. “World population growth” and “Land use”. Retrieved from “Our world in data” online database (https://ourworldindata.org; accessed on 3 May 2021). (**C**) Seafood production for fisheries (i.e., the volume of fish catches landed by a country for all commercial, industrial, recreational, and subsistence purposes) and aquaculture (i.e., the farming of aquatic organisms including fish, mollusks, crustaceans, and aquatic plants) since 1960. (Source: United Nations and Agriculture Organization (FAO); extracted from https://ourworldindata.org/seafood-production; accessed on 3 May 2021)

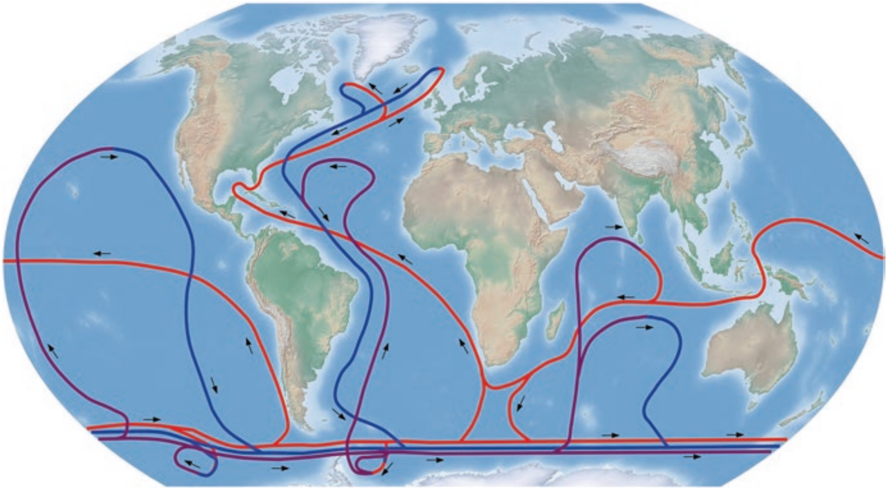

Fig. 3 Ocean conveyor belt indicating the flows and direction of warm surface (in red) and cold intermediate (in blue) and deep water (in purple). Mollweide projection map by Ktrinko, CC BY-SA 3.0. (https://commons.wikimedia.org/w/index.php?curid=11104534)

and sinks into the water column forming a current of cold, dense, deep intermediate and bottom water (blue and purple lines, respectively, in Fig. 3); then this water spreads and returns completing a full cycle in ca. 1000 years, as warm surface water (red line in Fig. 3). However, recent studies (Caesar et al. 2021) established a weakening of the Atlantic Meridional Overturning Current that is part of the conveyor belt, starting in the nineteenth century and followed by a more rapid decline during the last five decades. This slowdown is directly related to the warming process, causing more ice melting (Thornalley et al. 2018) and unusual winter wind patterns (Holliday et al. 2020) in the Arctic, hence altering ecosystems' dynamics and services. In addition, and although the excess of CO_2 released and accumulated in the atmosphere is partially taken up by the oceans (and other water bodies) and stored in marine sediments through the biological pump, it also causes acidification by reducing the pH (Sabine et al. 2004). In fact, approximately 0.1 pH units decreased in the World's ocean in the last 200 years (Raven et al. 2005) and is expected to be reduced by further 0.3–0.4 units if atmospheric CO_2 concentrations reach 800 ppmv (Orr et al. 2005), almost doubling the present concentration (Fig. 1B). Therefore, more acidic waters may accentuate the production of misshapen shells, reductions in calcification (e.g., coccolithophores, Riebesell et al. 2000), declines in growth and reproduction, and increases in mortality in calcifying species (Azavedo et al. 2015) but also alter the cycling of nutrients and many other elements and compounds in the ocean.

The complexity of global change implies that many other processes besides warming and acidification are likely going to affect organism and ecosystem functioning. Global warming leads to sea-level rise (Blunden and Arndt 2020) and ocean deoxygenation (Keeling et al. 2010; Oschlies 2021) and influences regional patterns of climate, being responsible for extreme rain and wind events (Seneviratne et al. 2012). Also, the abovementioned agricultural, urban, and industrial developments due to increasing human population have provoked an unprecedented pressure on aquatic systems, for example, by increasing the inputs of organic and inorganic nutrients, toxics, and pollutants into the water column (Paerl et al. 2014) and causing, among other effects, eutrophication (Rabalais et al. 2009; Glibert 2017), which in turn, is associated to the presence of more frequent and highly toxic phytoplankton blooms (Wells et al. 2020). These effects become especially relevant in coastal areas, which are considered as "entrance doors" for land-sea exchanges. However, and at the same time, coastal areas are hotspots of global total primary production (Cloern et al. 2014), fish production, and biodiversity and provide pivotal ecosystem services for humankind (e.g., water purification, coastal protection, recreation, and tourism) (Grizzetti et al. 2019). An interesting example of this type of coastal areas is Patagonia, in the southern tip of South America. The coastal areas of Atlantic Patagonia are characterized by very high biomass of primary producers, both at spatial and temporal scales (as estimated by chlorophyll-*a* concentration, Fig. 4A), yielding to prominent fisheries that unfold from the coast to the shelf break front (Fig. 4B enlargement). These fisheries export ca. US $1500 million per year, representing ~3% of Argentina total exports (www.indec.gob.ar), being the most important species in terms of annual catches the red shrimp *Pleoticus muelleri*, the Argentine hake *Merluccius hubbsi*, and the shortfin squid *Illex argentinus*. Even more, the coastal area of Patagonia also constitutes a huge reservoir of biodiversity (> 70 chromista, > 200 plant, and > 3000 animal species; Miloslavich et al. 2011).

Due to these particularities and the relevance of the Patagonian area, in this book, we focus on the changes that occurred in both short- and long-term temporal scales that shaped this regional anthroposphere. We also explore how coastal Patagonia has evolved over time, either as a result of natural variability or anthropogenic pressures. To accomplish this, we addressed several biological organization levels (i.e., from subcellular to an ecosystem level), trophic groups (i.e., from microbial plankton to top predators (large mammals and birds)), and abiotic components (i.e., physicochemical level) and provide predictions on how this area would respond in the future to global change. Finally, and despite the low population density of this coastal area, we evaluated how humans played a transcendental role as historical consumers and shapers of the coastal marine resources. This approach lies in that human footprint is leading the safe operating space for life on Earth to some planetary boundaries (e.g., biogeochemical flows "phosphorus, nitrogen", biosphere integrity "genetic diversity losses") (Rockström et al. 2009), accelerating the Anthropocene trajectory and pushing the Earth system away from the Holocene conditions. Thus, under this context, it has become necessary to evaluate what are the ecosystemic response thresholds to external perturbations to avoid reaching a no-return status that impairs the biologically and functionally diverse biosphere.

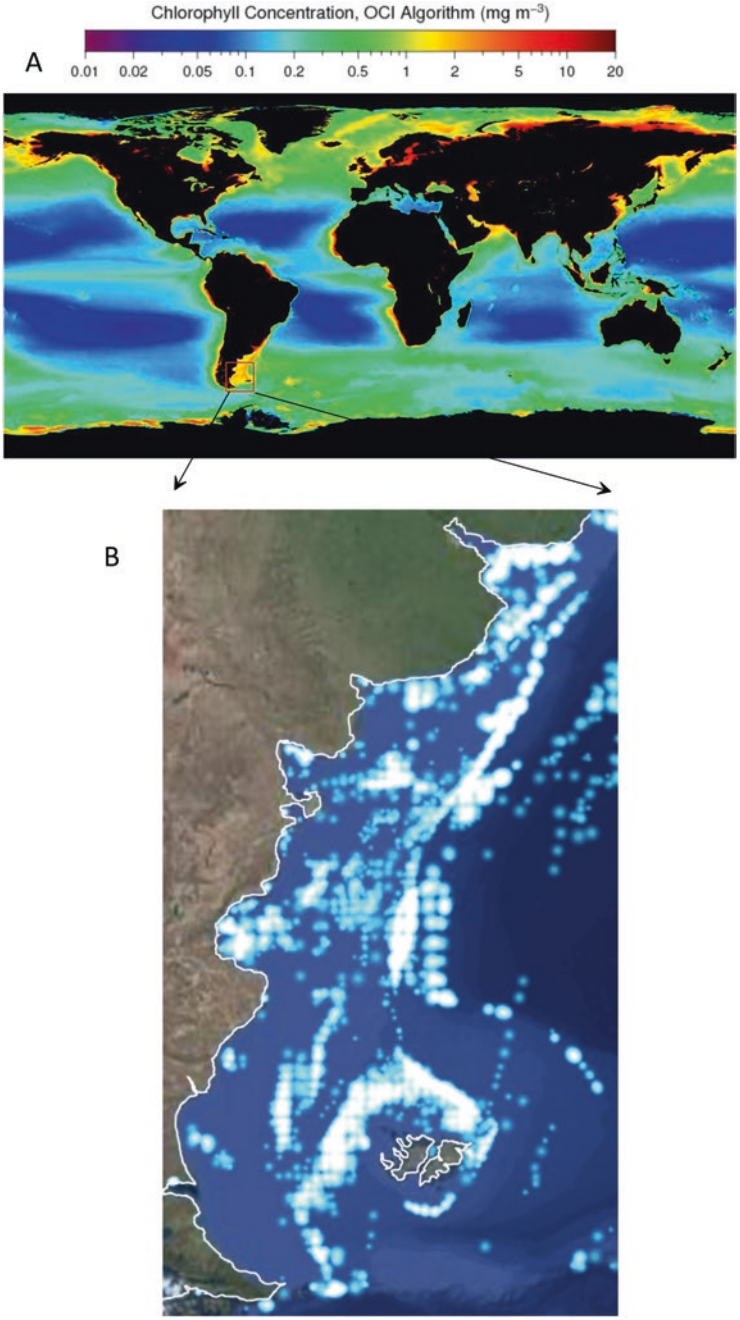

Fig. 4 (**A**) The map of surface chlorophyll concentrations retrieved from MODIS-Aqua satellite (2002–2020 period; resolution, 4 km; https://oceancolor.gsfc.nasa.gov). (**B**) Indicators of fishing activity (lower panel) by trawling footprints (whitish dots) for the period of March–June 2021. (https://globalfishingwatch.org/map) in the Southwest Atlantic

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“In calling up images of the past, I find that the plains of Patagonia frequently cross before my eyes; yet these plains are pronounced by all wretched and useless. They can be described only by negative characters; without habitations, without water, without trees, without mountains, they support merely a few dwarf plants. Why, then, and the case is not peculiar to myself, have these arid wastes taken so firm a hold on my memory?”

Charles Darwin (The voyage of the Beagle)

Part I

The Abiotic Environment of the Patagonian Coast

Climate Changes in Coastal Areas of Patagonia: Observed Trends and Future Projections

Natalia Pessacg, Josefina Blázquez, Julio Lancelotti, and Silvina Solman

Introduction

The Earth's climate has warmed up since the 1950s, and this climate change is unequivocal. The atmosphere and the oceans have warmed up, sea level has risen, and snow pack and ice cover have declined (Stocker et al. 2013). These changes can clearly be attributed to the increase in anthropogenic greenhouse gases (Stocker et al. 2013). In addition, several studies carried out over the last decades have shown that global warming has a strong impact on continental and oceanic ecosystems and on their services to human beings (Hoegh-Guldberg et al. 2018).

Changes in the climate system have impacted on coastal areas. The physical impacts on these zones can be divided into short and long timescale impacts (Wong et al. 2014). Floods, coastal erosion and coastal flooding, severe storms, and intense rainfall runoff are some of the physical impacts on coasts on a short timescale, while on longer timescales, they are due to the effects of climate change on wind and wave patterns. Global warming can also modify climate variability in a region, which in turn modulates local climate by affecting storm frequency (intensity and location),

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wind patterns, and wave climate (such as wave height, mean or peak period, and mean direction) (Wong et al. 2014) and related physical coastal processes (wave propagation, reflection, transmission, sediment transport) (Sierra and Casas-Prat 2014). These impacts on coastal areas are aggravated by human pressure associated with population growth trends in these areas. In many cases, human pressures may dominate over natural processes. As a consequence, coastal areas are influenced by human and climate drivers as well as by the complex interactions between them (Nicholls et al. 2007).

Changes in the physical climate drivers described above have been affecting the dynamics of biophysical and human systems in coastal areas of the region, and future climate change is expected to further affect the ecosystem functioning and services. In particular, in the Atlantic coastal area of Patagonia, we include several examples of impacts which are described in detail in the next chapters of this book. In this context, the coastal systems could be considered as vulnerable to changes in climate.

Within this frame of reference, the aim of this chapter is twofold: firstly, to present the main characteristics of climate in continental Patagonian coastal regions and secondly, to describe the physical changes in atmospheric variables and climate patterns which in turn could lead to changes in the Atlantic coastal Patagonian ecosystems.

Climate Characteristics of Coastal Areas of Patagonia

Regional Climate

Patagonia is located at the southern end of South America between the Atlantic and Pacific semipermanent subtropical anticyclones – situated at approximately 30° south of latitude – and north of the subpolar low-pressure trough. The climate in Patagonia is characterized mainly by the westerly flow and the effect of the Andes mountains. Indeed, the westerlies, defined as the prevailing winds from the west toward the east in the middle latitudes between 30°S and 60°S, are the main climatic feature in the midlatitudes of the Southern Hemisphere. Due to the surface pressure decreasing poleward, the strong low-level westerlies are predominant throughout the year south of 35°S with a maximum intensity between 45°S and 55°S (Fig. 1a) (Garreaud 2009). However, there is a high day-to-day variability in pressure and wind patterns in connection with the presence of migratory surface cyclones and anticyclones (Garreaud et al. 2009). In coastal areas, wind circulation patterns are strongly affected by the local phenomenon of sea breezes. In many coastal regions, sea breezes are the main wind circulation pattern during warm seasons. The sea breeze develops due to the differential heating of air over coastal areas and the adjacent sea water. This breeze occurs most often during the afternoon in the spring and summer months when the differential heating is higher. Since water heats up more

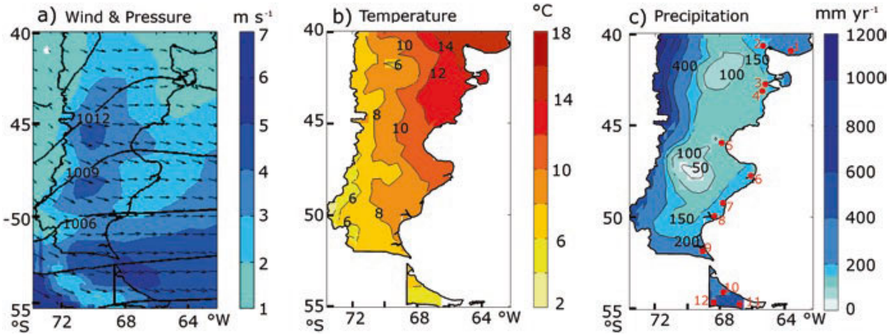

Fig. 1 (**a**) Wind direction (arrows), intensity (m s^{-1}, shaded), and mean sea-level pressure (hPa, black line) from ERA-Interim reanalysis (European Centre for Medium-Range Weather Forecast – ECMWF), average 1980–2009; (**b**) temperature (°C) at 2 m from CRU dataset (Climate Research Unit, University of East Anglia), average 1980–2009; (**c**) precipitation (mm yr^{-1}) and location of meteorological stations (red circles) from the National Meteorological Service of Argentina used in this chapter. All stations present altitudes lower than 150 m. (1) Viedma; (2) San Antonio Oeste; (3) Puerto Madryn; (4) Trelew; (5) Comodoro Rivadavia; (6) Puerto Deseado; (7) San Julián; (8) Puerto Santa Cruz; (9) Río Gallegos; (10) Río Grande; (11) Tolhuin; (12) Ushuaia. (Adapted from Coronato et al. 2017)

slowly than land, the air over the land becomes warmer than the air over the ocean which results in a difference in atmospheric pressure between land and water. The sea breeze flowing during the day compensates this atmospheric pressure difference by moving air from the higher pressure over the water to the lower pressure over the land. The strength of the sea breeze depends on the temperature differences. At night, land cools down faster than water, and the land breeze compensates the atmospheric pressure differences. It can develop into sea breeze fronts (Olcina Cantos and Azorín Molina 2004) which play a key role in rainfall patterns (Ellis and Chen 2004). Sea breeze also tends to decrease the effect of the urban heat island intensity and magnitude in large cities located in coastal areas (Takebayashi 2020), which in turn has a relevant effect on human comfort (Lopes et al. 2010). Despite the relevance of this phenomenon, there are not many studies investigating the effects of the sea breezes on coastal areas in Patagonia. Scian (1976) studied the occurrence of sea breezes from October to March for a particular year in Puerto Madryn. This author found that sea breeze occurred 42% of the days and that onshore flow can reach up to 20 km inland. Dellatorre et al. (2012) found that in Nuevo gulf, northern Patagonia, diurnal sea water temperature fluctuations were explained by sea breezes which forced consecutive downwelling-relaxation periods. The breezes also could be relevant as a transport mechanism for coastal organisms at larval stages. Coronato (1995) studied the sea breezes' cooling effect in Puerto Madryn as the main bioclimatic factor that smooths seasonal differences. Regarding cloud cover, the intensification of the Southern Hemisphere westerlies in summer leads to high cloud cover in southern Patagonia. The opposite happens in northern Patagonia where the southward shift of the subtropical anticyclone favors a decrease in cloud cover during summer (Castañeda and González 2008).

The temperature in Patagonia presents a northeast-southwest gradient in concordance with the latitude and altitude effects, and it is also related to the predominant wind patterns (Fig. 1b). In most of the region, the westerlies tend to decrease the amplitude of the annual cycle of temperature. In coastal areas the sea breezes play a key role in moderating the temperature cycle. The wind chill, the effect of wind over perceived temperature, which is more intense during summer, leads to the perception of the climate of this area as more oceanic than it actually is (Coronato 1993).

Regarding precipitation, coastal areas of Patagonia are located in arid and semi-arid midlatitude regions with an average annual rainfall below 200 mm yr^{-1} (Fig. 1c) and with a high interannual variability. The few rainfall events are caused mainly by frontal systems and cyclone activity related with incoming troughs from the South Pacific (Bell 1981; Jobbagy et al. 1995; Barrett et al. 2011; Catto et al. 2012; Dowdy and Catto 2017; Blázquez and Solman 2018). One of the regions of genesis of cyclone activity was found near the southern coast of Patagonia (Hoskins and Hodges 2005; Gramcianinov et al. 2019; Lakkis et al. 2021), mainly associated with baroclinic instability (see Holton 1992 for references about this hydrodynamic instability). The frontal systems tend to be more intense when the westerlies are weaker (Garreaud et al. 2013). Besides that, a recent study found other mechanisms that could generate precipitation events over the coastal regions of Patagonia related with the anomalous presence of easterly winds along the coast (Agosta et al. 2019, 2020). The authors found that in Comodoro Rivadavia City, when persistent easterlies affect the Patagonian coast, rainfall events are registered. Though this is not a frequent situation, this behavior is related to blocking flow events which permit convergence of westward moisture flux from the Atlantic. Intense daily precipitation events are also relevant in coastal areas. The total rainfall recorded during these events can represent, on average, >40% of the mean annual precipitation (Bilmes et al. 2016). These extreme events are mainly related with the natural variability of the climate system but also with climate change (Stocker et al. 2013). Moreover, the occurrence of easterly winds over the Patagonian coast could play a role in this kind of precipitation events in central and coastal areas of Patagonia (Agosta et al. 2015). The local contribution of strong moisture transport from the Atlantic ocean could exceed the drying effect of the westerlies. This could explain a fraction of intense precipitation due to the slow-moving weather systems crossing over Patagonia (Agosta et al. 2015).

Compound extreme events of precipitation and temperature were evaluated by Olmo et al. (2020). The authors found that in coastal areas of Patagonia, cold days and heavy precipitation have a significant and positive relationship probably related to the passage of cold fronts, especially during winter. Despite this kind of extreme precipitation occurring only a few times, it is highly influenced by the temperature extreme events. These heavy rainfall events have caused unprecedented damage in Patagonia such as urban flooding, rivers overflow, loss of lives, population displacement, physical damages, and adverse effects on basic ecosystem services such as water (quality and quantity) and food production (Bilmes et al. 2016; Kaless et al. 2019; Paredes et al. 2020). The magnitude of the impact of this kind of extreme precipitation events is related not only with the magnitude and intensity of rainfall but also with the level of population vulnerability and the exposure to the event (Cardona et al. 2012).

In addition, the Patagonian coast, as most of the arid and semiarid regions of the world, is characterized by extreme dryness conditions due to scarce rainfall and high potential evapotranspiration (due to the intense winds) (Prohaska 1976) and suffers prolonged and frequent droughts (Le Houérou 1996; Gaitan et al. 2014). These extreme hydrometeorological events are perceived as one of the costliest in southern South America in socioeconomic and environmental terms (Rivera et al. 2018 and references therein). In eastern Patagonia, the recurrent droughts, the high evapotranspiration rates larger than precipitation rates (Alvarez et al. 2013), and the strong winds are the natural causes that mostly enhance the strong desertification process – land degradation in arid, semiarid, and dry subhumid areas – in the region (Le Houérou 1996; Voigt Beier et al. 2016). In general, droughts in Patagonia are related to anomalous anticyclonic activity over the Pacific (Minetti et al. 2010). One of the most damaging drought events studied in the region was the persistent event which occurred during 1988–1989, due to its greatest temporal and spatial extension (Rivera and Penalba 2014).

Climate Singularities of Coastal Areas

Meteorological data collected in weather stations of 12 main coastal cities of Patagonia (Fig. 1c) were analyzed to characterize the climate of this region. The data series, provided by the National Meteorological Service, includes the period of 1979–2019, although it is shorter for some meteorological stations and variables as depicted in the figures below. Data quality analysis was performed for the entire series (temperature, precipitation, and wind). All months with less than 15 daily records and all years with less than 10 months of data were excluded from the analysis.

The data indicated a strong temperature gradient along the latitudinal axis. As expected, the highest temperatures were recorded in northern coastal areas (i.e., Viedma, San Antonio Oeste, and Puerto Madryn weather stations), while the lowest values were recorded in the southern tip of the region between Río Gallegos and Ushuaia (Table 1). Mean temperature ranges from 15.4 to 4.8 °C from north to south continental coastal areas of Patagonia. Additionally, percentiles 5th and 95th were computed for minimum and maximum temperatures, respectively, at every weather station to evaluate extreme cold and hot days. Extreme minimum temperatures in coastal regions are characterized in general for temperatures < -1 °C with the lowest values recorded in Tolhuin (< -6.4 °C). Besides, on extremely cold days, the maximum temperature in Tolhuin and Río Grande barely reaches 0 °C (not shown). On the other hand, extreme maximum temperatures >30 °C were recorded in the northern coastal area of Patagonia due to the latitudinal effect, with the maximum value recorded in San Antonio Oeste (>33 °C, Table 1).

Table 1 Temperature (°C), precipitation (mm), and winds (km h^{-1}) statistics for historical periods of meteorological stations located in coastal areas of Patagonia

	Temperature			Precipitation			Wind			
Station	mean T	P5 Tmin	P95 Tmax	mean PP	P95 PP	P99 PP	mean W	P25 W	P95 W	max W
Viedma	14.6	−1.4	32.7	357.5	17.0	37.4	21.0	14.8	37.3	71.0
San Antonio Oeste	15.4	−2.0	33.9	270.0	19.8	41.1	21.1	15.2	35.8	73.2
Puerto Madryn	15.1	−1.4	30.8	197.9	14.0	32.9	23.6	17.3	39.9	69.7
Trelew	13.7	−2.0	32.0	210.4	12.0	29.0	21.7	14.8	39.0	76.8
Comodoro Rivadavia	13.1	0.3	28.9	245.9	11.0	28.7	22.7	14.3	43.7	84.8
Puerto Deseado	11.1	−1.2	26.0	206.7	8.0	16.0	31.8	22.0	56.1	89.0
San Julián	10.2	−2.4	26.0	246.1	10.0	20.0	28.2	19.0	51.7	88.3
Puerto Santa Cruz	9.5	−3.3	24.2	179.7	10.0	20.0	26.6	15.0	55.7	118.0
Río Gallegos	7.8	−4.2	22.2	282.2	8.4	16.0	25.0	15.5	49.0	109.5
Río Grande	5.7	−5.6	17.8	318.8	8.0	15.0	23.6	14.6	43.0	76.3
Tolhuin	4.8	−6.4	15.0	571.0	10.0	18.1	–	–	–	–
Ushuaia	5.9	−2.4	16.6	463.7	9.0	17.0	20.3	11.3	42.5	77.5

Abbreviations: *mean T* mean temperature, *P5 Tmin* fifth percentile of minimum temperature, *P95 Tmax* 95th percentile of maximum temperature, *mm* yr^{-1} *mean PP* mean annual accumulated precipitation, *P25 PP and P99 PP* 95th and 99th percentiles of daily precipitation, respectively, *mean W* the average of intensity mean wind, *P25 W* and P95 W 25th percentile and 95th percentile of intensity mean wind, respectively, *max W* maximum record of intensity mean wind

Precipitation in coastal areas of Patagonia evidences a clear difference between the provinces located over the northern and southern part of the region (Table 1). Over Río Negro, Chubut, and Santa Cruz, the Andes retain most humidity, generating extreme gradients from west to east (Jobbagy et al. 1995), resulting in scarce rainfall in the coastal areas (ranging from 180 to 350 mm yr^{-1}, Table 1). In contrast, the decreasing altitude of the Andes at higher latitudes, which are also twisted to the west (Peri et al. 2013), reduces the influence of this orographic barrier over Tierra del Fuego, allowing a higher humidity transport which is clearly reflected in the observed precipitation, ranging from 320 to 570 mm yr^{-1} in the three southernmost weather stations (Table 1). The 95th and 99th percentiles of daily precipitation were calculated to evaluate extreme precipitation events (Table 1). The coastal regions are characterized by a scarce amount of precipitation with daily events of <5 mm day^{-1} (Beltrán 1997), and the events defined by the 95th percentile are relatively weak with <20 mm day^{-1}. The 99th percentile indicates a proportion of 1% of occurrence of daily precipitation events with magnitudes over 30 mm along a year in northern coastal areas. Although these events are relatively weak, they mark the difference between wet and dry years (Golluscio et al. 1998). As previously mentioned, due to the inherent characteristics of the region and their urban development, extreme precipitation events may cause, depending on their intensity, significant damage in coastal areas. In particular, precipitation events >50 mm day^{-1}, which have a return period of approximately 4 years, produce urban and rural flooding, causing substantial damage in infrastructure and affecting the provision of drinking water (Bilmes et al. 2016; Kaless et al. 2019).

The statistical analysis of wind intensity shows that, on average, wind intensity in coastal areas is of the order of 20 km h^{-1}. The average maximum ranges from 69.7 km h^{-1} in Puerto Madryn to 118 km h^{-1} in Puerto Santa Cruz (Table 1), while the recorded maximum for the historical period ranges from 89 km h^{-1} in Puerto Madryn and San Antonio to 181 km h^{-1} in Comodoro Rivadavia (not shown). The analysis based on percentiles of the daily wind data indicates that there is an average of 25% of days with winds >30 km h^{-1} in coastal cities, with the maximum values in Puerto Deseado (> 40 km h^{-1}). Relative frequencies for wind direction (Fig. 2)

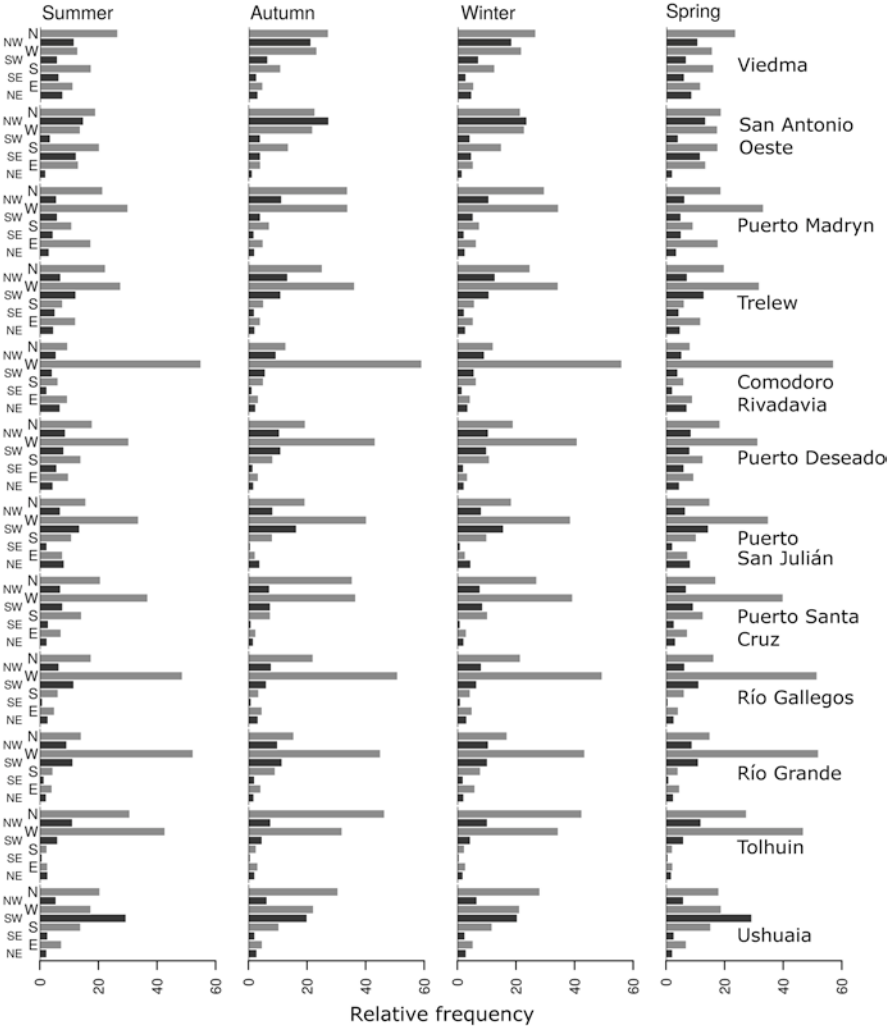

Fig. 2 Seasonal relative frequency of wind direction for each station

indicate a clear west component for most of the cities along the year, although in some locations a north component is also frequent due to the influence of the Atlantic anticyclone. In the northern (San Antonio Oeste and Viedma) and southern (Tolhuin and Ushuaia), the north or northwest component is as important as the west wind component. Results also show that the most extreme wind conditions are recorded in the coastal towns of Santa Cruz province (Puerto Deseado, Puerto Santa Cruz, San Julián, and Río Gallegos) and Tierra del Fuego (Río Grande and Ushuaia). Southern of Comodoro Rivadavia wind intensity exceeds 40 km h^{-1} at least 25 days per year on average (Table 1).

Influence of Large-Scale Variability Patterns on Climate

The large-scale circulation variability affecting Patagonian climate is dominated by three main patterns: the Southern Annular Mode and two Pacific-South American patterns, referred to as PSA1 and PSA2.

The Southern Annular Mode (hereafter SAM), often referred to as the Antarctic Oscillation (AAO), is associated with quasi zonally symmetric synchronic pressure anomalies of the opposite sign over high and midlatitudes of the Southern Hemisphere (Thompson and Wallace 2000; Marshall 2003; Marshall and Thompson 2016 and references therein): when pressures are anomalously high over Antarctica, the SAM is defined as being in its positive phase and vice versa. The SAM is also frequently characterized by latitudinal shifts in the midlatitude jet. Hence, this mode is linked to variations in the intensity of the zonal mean wind. The SAM emerges as the leading mode of variability of the extratropical geopotential height anomalies, explaining roughly a 30% of the extratropical Southern Hemisphere atmospheric circulation variability (Kidson 1988; Thompson and Wallace 2000), and owes its existence to internal atmospheric dynamics in the midlatitudes of the Southern Hemisphere. Various methods have been used in the literature to define an index characterizing the SAM behavior. One of these methods is based on the principal components arising from an Empirical orthogonal function-based approach (Thompson and Wallace 2000). Another approach is based on normalized differences between zonally averaged monthly anomalies of mean sea-level pressure between two latitude bands, 40°S and 65°S, either based on gridded data or station data (Gong and Wang 1999; Marshall 2003). An example of this SAM index behavior computed from station data is displayed in Fig. 3. From this figure it can be noted that the SAM displays strong seasonal dependence with the largest intensity during the austral summer. Moreover, the SAM is characterized by interannual and inter-decadal variations. SAM interannual variability is influenced by tropical SST variability, particularly with the tropical Pacific and the ENSO variability (Fogt and Bromwich 2006). The SAM influence on South American climate has been the subject of several studies (Gillett et al. 2006; Gupta and England 2006; Dätwyler et al.

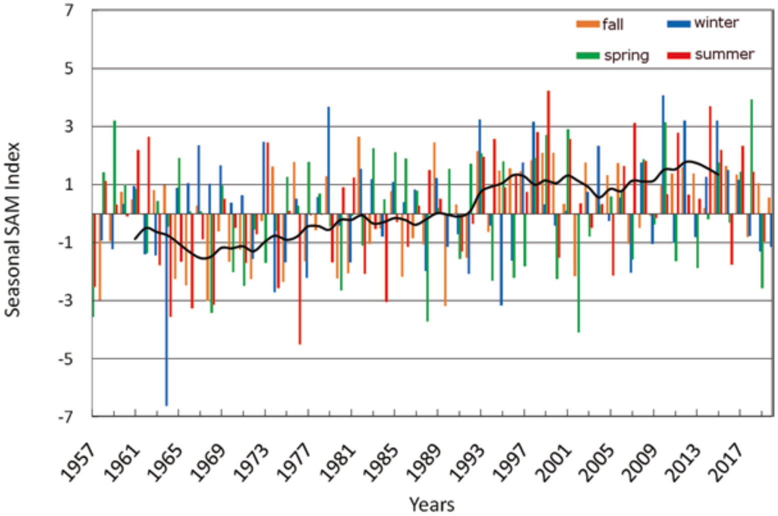

Fig. 3 Seasonal values of the observation-based SAM index. Colored bars correspond to each season: orange for the austral autumn (March–April–May), blue for the austral winter (June–July-August), green for the austral spring (September–October–November), and red for the austral summer (December–January–February). The smooth black curve shows filtered (5-year running mean) annual SAM index. (The SAM index data downloaded from https://legacy.bas.ac.uk/met/gjma/sam.html)

2018; Fogt and Marshall 2020 and references therein). These studies highlight that the positive (negative) phase of the SAM is associated with warm (cold) and dry (wet) conditions over southern South America, based on both gridded products and station data. Gillett et al. (2006) also showed that the positive sea-level pressure anomalies over Patagonia associated with the positive phase of the SAM induce large-scale descending air that may explain the warming and drying response. Moreover, the relationship among surface climate variables and the SAM has a strong seasonal dependence, being the warming response described above more prominent during the austral summer season.

The PSA patterns arise as the second and third modes of variability of the Southern Hemisphere atmospheric circulation accounting for roughly 25% of the total variance. These two modes are characterized by zonally asymmetric anomalies of the atmospheric circulation with maximum amplitudes in the Pacific ocean and associated with a propagating wave train within the Pacific-South American sector (Karoly 1989; Ghil and Mo 1991). The two PSA modes of variability, namely, PSA1 and PSA2, are in quadrature each other and are associated with anomalous convection in western and central tropical Pacific, respectively (Mo and Higgins 1998). The PSA pattern exhibits variability on a wide range of temporal scales, from the intraseasonal to interannual and decadal timescales. On the interannual timescales, PSA1 resembles the response of the Southern Hemisphere circulation to El

Niño-Southern Oscillation (ENSO) variability (Mo and Paegle 2001). Accordingly, the most relevant impacts of PSA modes on Patagonian climate are associated with the ENSO response, namely, wetter (drier) conditions for El Niño (La Niña) events during winter and spring seasons (Garreaud et al. 2009; Cai et al. 2020). Berman et al. (2012) also found that rainfall anomalies over the southern part of eastern Patagonia are linked with the presence of an anomalous cyclonic circulation associated with the PSA mode at the interannual timescales. ENSO teleconnections are also relevant in modulating the easterly moisture flux over the eastern Patagonian coast, as suggested by Agosta et al. (2019).

ENSO teleconnections are also modulated by lower-frequency climate modes, such as the Pacific Decadal Oscillation (PDO) so that the combined effect of both ENSO and the PDO also modulate the precipitation behavior at the regional scale over Patagonia (Kayano and Andreoli 2007). The PDO is the leading pattern of the sea surface temperature variability in the tropical to midlatitude Pacific ocean and is characterized by decadal to multidecadal variations (Newman et al. 2016). The PDO anomaly SST pattern displays a dipole structure with anomalies of the opposite sign over the tropical Pacific and midlatitudes in both hemispheres, though the northern Pacific anomalies are stronger than the southern Pacific counterparts.

Observed Climate Variability and Trends in Coastal Areas of Patagonia

Regional Scale

Over the last years, many studies have addressed observed and projected climate change at the global scale. However only few and dispersed studies have focused on climate change over Patagonia. The National Communications of Climate Change (NCCC, Barros 2006; Barros et al. 2014) is only one of the few initiatives devoted to assess climate change over different regions of Argentina. The NCCC reported an average warming of 0.4 °C for the 1960–2010 period for the entire Patagonian region, which is in agreement with previous studies (Rosenblüth et al. 1997; Villalba et al. 2003; Vincent et al. 2005; Boninsegna et al. 2009). Observed mean temperature changes in Patagonia could be related with the occurrence of warm events (Rusticucci and Barrucand 2002). However, the NCCC reported no significant warming signal for the coastal regions of north Patagonia and the southern coastal area of Santa Cruz and even a cooling of around 0.5 °C for the coastal areas of Río Negro. In addition, Rusticucci and Barrucand (2004) and the NCCC reported no significant observed trends for minimum temperature, but significant positive observed trends for the maximum temperature in coastal areas of Patagonia were found.

Regarding precipitation, previous studies have found no significant changes over the last 50 years in coastal areas of Patagonia. This could be associated with the scarce precipitation values and the high interannual variability in the region which overrides long-term changes. An exceptional behavior was analyzed by Castañeda and González (2008) in northern coastal areas of Patagonia (around Valdés peninsula) and southeast of Santa Cruz, where significant positive observed trends of precipitation were found during the 1950–1999 period. This is in agreement with the poleward shift of the precipitation belt over extratropical latitudes that has been observed in recent years, increasing the wetter conditions over southern Patagonia, especially in the cold season. Many authors have documented this shift (Wang et al. 2006; Solman and Orlanski 2014, 2016), finding a relationship with observed changes in the storm tracks, cyclone activity, and frontal systems which are in turn associated with the observed shift of the westerlies.

Furthermore, climate change exacerbates extreme hydrometeorological events such as heavy precipitation and drought (IPCC 2012). During 2017, for example, an unprecedented extreme precipitation event occurred in southern coastal areas of Chubut province, with the epicenter in Comodoro Rivadavia city, illustrating not only the social and economic local impacts of this kind of phenomena but also the effect on ecosystem services and their connection with other regions. Comodoro Rivadavia registered a total precipitation of 399 mm in the period March 29th to April 8th of 2017 (233 mm during the first 2 days). These persistent and heavy rains caused the worst floods in the history of the city (Paredes et al. 2020) and also activated the Chico river (affluent of the Chubut river) that had been dry for 80 years (Kaless et al. 2019). As a consequence, large amounts of sediments accumulated on the Chico river were transported into the Chubut river's main course limiting the water supply of 250,000 people for more than 20 days in the lower river region (300 km away from the precipitation event's epicenter) (Kaless et al. 2019).

In coastal areas of Patagonia, Barros (2006) showed that the frequency of extreme precipitation (> 50 mm in 48 h) increased in the coastal regions north of Comodoro Rivadavia during the period 1959–2003. This is in agreement with the results found by Robledo (2012) who showed an increase of observed daily precipitation events larger than 75th percentile in Trelew during summer and autumn, while during spring negative changes were documented.

On the other hand, several studies have found that the extent, severity, duration, and frequency of droughts are increasing as a consequence of climate change (Dai 2012). Particularly, in Patagonia, the number of drought events has increased, and changes in the mean drought duration are expected for the twenty-first century (Penalba and Rivera 2013, 2016). Besides that, Gaitan et al. (2014) suggest that climate change and species loss (related with global warming) could increase the vulnerability of Patagonian ecosystems to drought.

Other relevant impacts of climate change on coastal areas are the variations in sea surface temperatures, sea level, and coastal erosion which are assessed in other chapters of this book. Global sea-level rise impacts on coasts and exacerbates coastal erosion and flooding in coastal areas of Argentina (Schnack et al. 2010). Saraceno et al. (this volume) shows linear trends ranging between 2 and 5 mm yr^{-1} for sea surface height in the Patagonian coasts during the period 1993–2020. The action of waves at higher elevations due to the sea-level rise could derive in some regions in coastal erosion processes. Isla and Isla (this volume) describe that coastal areas with availability of gravels derived from the Andes would protect bays, marshes, and estuaries from the erosion effects, but those areas where sand deposits become dominant would be more susceptible to coastal erosion. In addition, storm surges enhance most of the severe erosion processes which in turn are aggravated by sea-level rise (D'Onofrio et al. 2006). Patagonian coastal areas have suffered several storm surges basically produced by the joint action of the semipermanent Pacific anticyclone and a cyclone located over the Atlantic. This situation is related to strong winds from the south or southeast and high water levels that affect the Patagonian coast (Schnack et al. 2010). This storm surge has coincided with heavy precipitation events in coastal cities of the region (such as Comodoro Rivadavia or Rawson). This natural phenomenon, together with vulnerability population situations, is a high factor of risk for some coastal areas of Patagonia (Gómez et al. 2003; Massera 2019).

Local Scale

In this chapter observed climate variability and trends in Atlantic coastal locations of Patagonia were analyzed using meteorological stations' recorded data for 12 coastal cities as described above (Fig. 1c). The nonparametric Mann-Kendall test was used for each variable to evaluate significant trends in the mean annual temperature, precipitation, and wind intensity, respectively, for the period 1979–2019. Data were square root transformed for variance homogenization. Autocorrelation functions were calculated for the three climatic variables to test the occurrence of repeating patterns in the time series.

Anomaly temperature series showed a strong interannual variability in most of the weather stations analyzed, and there was no evidence of a clear trend for the coastal stations considered (Fig. 4). There were significant positive trends for annual mean temperature in Trelew and Puerto Deseado, while significant negative trends for San Julián and Río Gallegos were found (Fig. 4). Seasonal analysis (not shown) indicated a significant negative trend for spring temperatures in many coastal locations (Ushuaia, Tolhuin, Río Gallegos, Trelew, and San Antonio). This coastal spring cooling, in contrast to the global warming trend, plays a key role in keeping coastal temperature conditions close to historical periods in a context of global climate change. These results are in agreement with previous studies in the region. In other regions of the world, a similar behavior was found associated with different dynamical and large-scale mechanisms (Falvey and Garreaud 2009; Li and Wang 2013).

Anomalies of precipitation in coastal areas of Patagonia show a clear interannual variability (Fig. 5), a typical behavior of precipitation in this region (Saurral et al. 2017). Analysis of precipitation data indicate significantly negative trends for

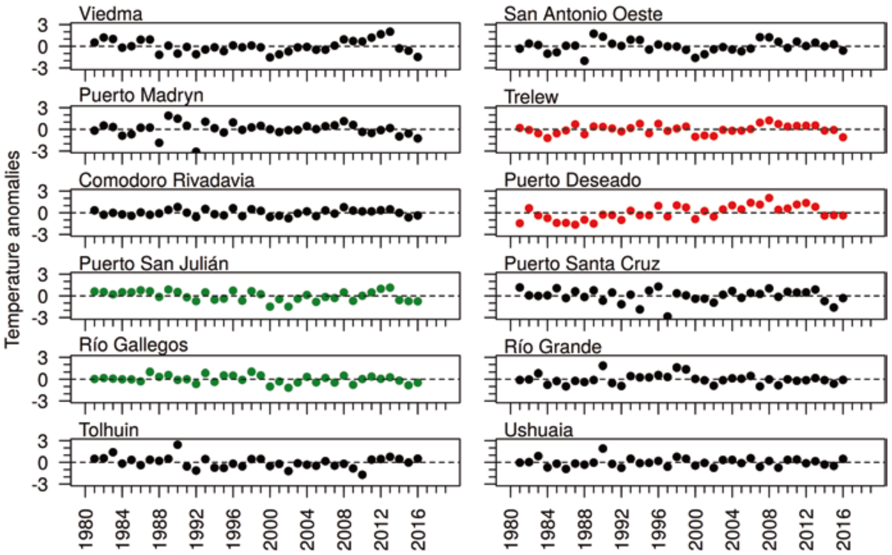

Fig. 4 Historical annual temperature anomalies (°C) for Atlantic coastal Patagonian cities. Anomalies were calculated as the difference between the temperature value for each individual year and the long-term average value of each series. A positive (negative) anomaly indicates that the temperature was warmer (cooler) than the mean temperature of that series. Statistically significant positive (negative) trends are shown in red (green). Series with no significant trends are in black. Significance was assessed through a Mann-Kendall test with the level of significance set at $\alpha < 0.1$. (Details of the methodology applied could be found in Hamed and Rao 1998)

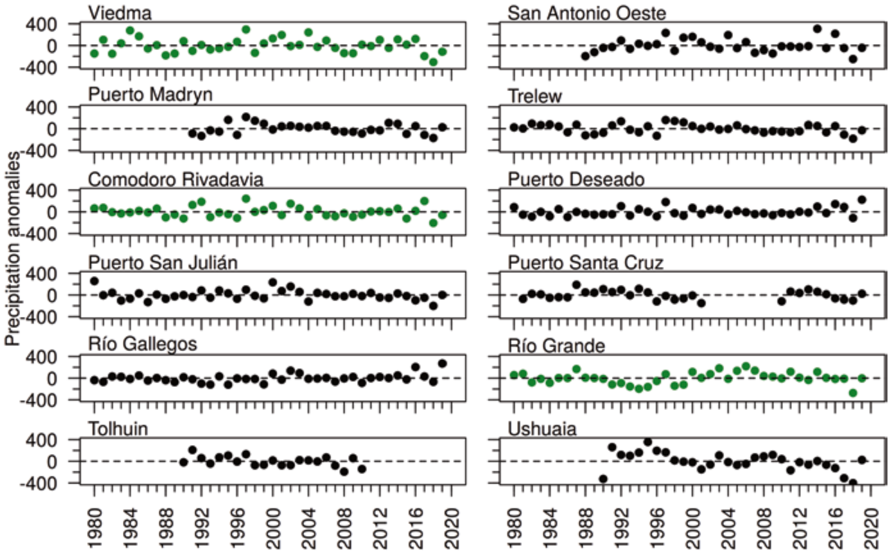

Fig. 5 Historical annual precipitation anomalies (mm yr^{-1}) for Atlantic coastal Patagonian cities. Anomalies were calculated as the difference between the precipitation value for each individual year and the long-term average value of each series. A positive (negative) anomaly indicates wetter (drier) conditions for that year with respect to the mean precipitation of that series. Statistically significant negative trends are shown in green. Series with no significant trends are in black. Significance was assessed through a Mann-Kendall test with the level of significance set at $\alpha < 0.1$. (Details of the methodology applied could be found in Hamed and Rao 1998)

Viedma, Comodoro Rivadavia, and Río Grande. Previous results for a shorter period of time (1967–1998) showed positive precipitation linear trends in southern Santa Cruz stations (Barros 2006) that are not evident for the historical records (with more than 35 years in most of the stations) analyzed in this work with Mann-Kendall test. By contrast, Saurral et al. (2017) found significant positive trends using the Mann-Kendall test for precipitation in Trelew for the centennial time series for the period 1902–2013 and no significant trends for Comodoro Rivadavia for the historical time series covering the period 1913–2013. This means that trend analysis is very sensitive to the period considered due to the large interannual variability of precipitation in the region, the position and strength of the South Atlantic anticyclone (Doyle and Barros 2002; Saurral et al. 2017), and the influence of large-scale climate variability modes that are superimposed to trends and also control precipitation in the region.

Regarding wind intensity, there are significant negative trends in six of the coastal cities of the region (Fig. 6), while the others showed no significant trends. In the series analyzed, positive trends were not found, differing from previous studies done with MERRA reanalysis (Bianchi et al. 2017), where the authors found

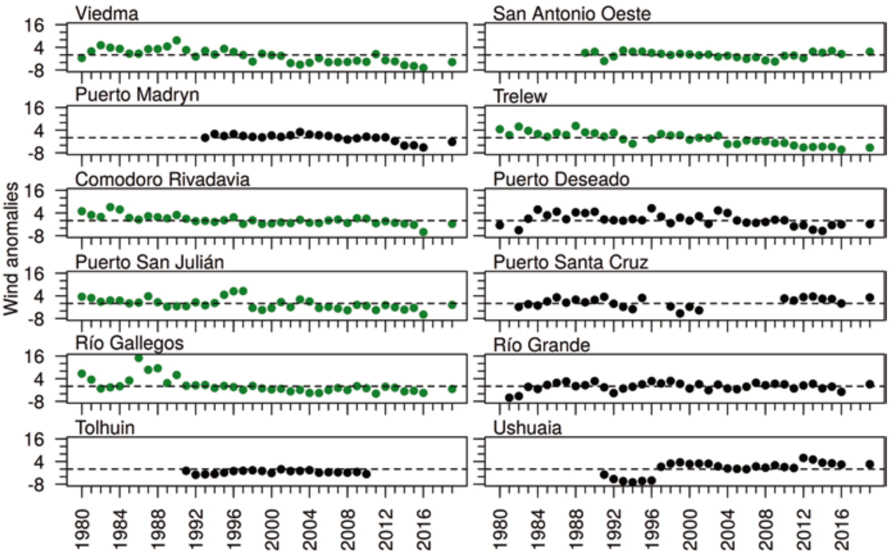

Fig. 6 Historical annual intensity wind anomalies (km h^{-1}) for Atlantic coastal Patagonian cities. Anomalies were calculated as the difference between the wind intensity value for each individual year and the long-term average value of each series. A positive (negative) anomaly indicates stronger (drier) intensity winds for that year with respect to the mean wind intensity of that series. Statistically significant negative trends are shown in green. Series with no significant trends are in black. Significance was assessed through a Mann-Kendall test with the level of significance set at $\alpha < 0.1$. Details of the methodology applied could be found in Hamed and Rao (1998). The dashed lines represent zero values

positive wind intensity trends south of 44°S. Differences are probably due to the low spatial resolution of this reanalysis dataset and that the trends were calculated for winds at 50 m, whereas the meteorological station measurements are at 10 m.

Since Patagonia is characterized by strong winds, it is relevant to analyze indices to comparatively quantify and evaluate their incidence at local and regional scales and the trends of these extreme situations. In particular, in this chapter, the number of days with wind intensity higher than the 95th percentile and the number of days with wind intensity >50 km h^{-1} (selected as a threshold for intense wind speeds) were calculated for each station to analyze trends in the frequency of extreme wind events in coastal areas (Fig. 7). The most extreme wind conditions are located in southern coastal areas where wind intensity exceeds the threshold of 50 km h^{-1} (open circles in Fig. 7) at least 25 days per year, on average. In fact, the 50 km h^{-1} threshold is below the records of the 95th percentile (filled circles in Fig. 7), indicating that wind intensities >50 km h^{-1} are highly frequent in these areas. On the other hand, in the northern coast and in the southern tip of the region, mean wind intensity exceeds the 50 km h^{-1} threshold only 1 or 2 days per year. The number of days with wind intensity >50 km h^{-1} is significantly smaller for the historical periods in most of the stations, except for the southern tip of the region and San Antonio Oeste. Similar results are found for the index defined as the number of days with mean intensity wind higher than the 95th percentile (Fig. 7).

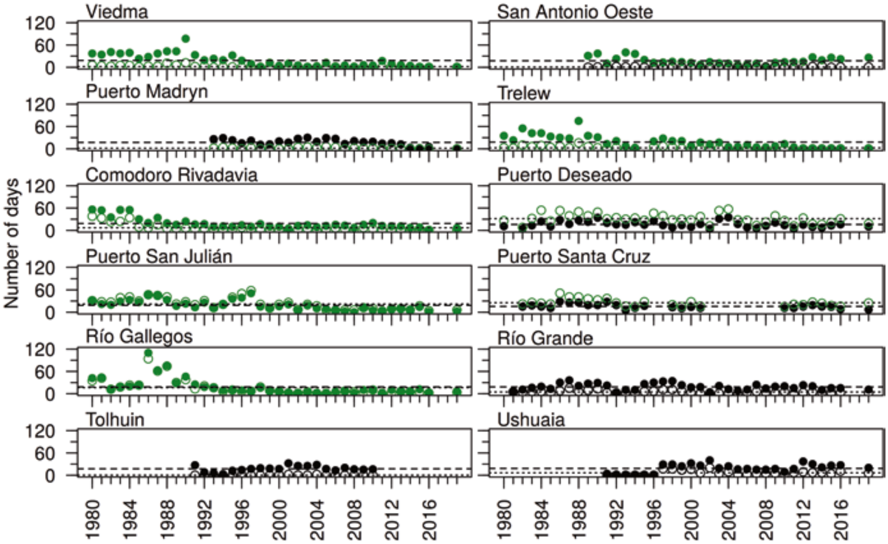

Fig. 7 Number of days with wind intensity higher than the 95th percentile (filled circles) and number of days with wind intensity higher than 50 km h^{-1} (open circles) for each station. Statistically significant negative trends are shown in green. Series with no significant trends are in black. Significance was assessed through a Mann-Kendall test with the level of significance set a $\alpha < 0.1$. Details of the methodology applied could be found in Hamed and Rao (1998). Dashed and dotted lines represent the mean values of the 95th percentile and higher than 50 km h^{-1} series, respectively

Ozone Trends and Climate

Ozone is a natural gas in the atmosphere and plays a relevant role in the climate system. It is a greenhouse gas, thereby warming the troposphere and the stratosphere due to its role in absorbing solar ultraviolet radiation (UV). This last effect protects life on our planet due to the absorption of damaging UV radiation by the stratospheric ozone layer (Pyle et al. 2005). However, the stratospheric ozone depleted in recent decades due to human-related emissions of ozone-depleting substances (ODSs) and the subsequent release of reactive halogen gases (Engel et al. 2018). In 1987, the Montreal Protocol, an international agreement to protect the climate system of chemicals that deplete the ozone, was signed. As a consequence of this protocol, a decline in stratospheric concentrations of ODSs around the globe and a recovery of the stratospheric ozone were recorded, in particular over Antarctica where extreme ozone depletions were registered, referred to as the ozone hole (Engel et al. 2018).

Changes in ozone column concentration influence not only the stratosphere but also the troposphere, modifying the solar UV reaching the Earth's surface and affecting the large-scale circulation. In the last decades, it was demonstrated that the ozone depletion was the main cause of changes in atmospheric circulation of the Southern Hemisphere (Thompson et al. 2000, 2011; Thompson and Solomon 2002; Gillett and Thompson 2003; Perlwitz et al. 2008; Son et al. 2008; Previdi and Polvani 2014, and references therein). These studies highlighted the ozone depletion as one of the drivers of the poleward shift and strengthening of the tropospheric jets in the Southern Hemisphere, often referred to as a positive trend of SAM (described above), and the poleward expansion of the summertime southern edge Hadley cell (Thompson et al. 2000; González et al. 2014; Engel et al. 2018; Barnes et al. 2019). These physical mechanisms can explain part of the increase in the mean and extreme precipitation and the decrease in extreme temperatures over southeastern South America, including the Patagonian north coast (González et al. 2014; Wu and Polvani 2017; Damiani et al. 2020). Moreover, several authors showed that during the second half of the twentieth century, the impact of ozone depletion on the Southern Hemisphere climate was larger than that of increased greenhouse gases (McLandress et al. 2011; Polvani et al. 2011; Lee and Feldstein 2013). Additionally, it is worth noting that stratospheric ozone depletion interacts with climate change with consequences on food and water security, human well-being, and ecosystem sustainability, as described in detail by Barnes et al. (2019).

The climate impacts of ozone depletion are expected to reverse over the coming decades as stratospheric ozone recovers (Engel et al. 2018). Modelling studies suggested that the recovery of stratospheric ozone in the Antarctic region to the 1980s levels would occur around 2060–2065 (WMO 2014, 2018; Dhomse et al. 2019). In coastal areas of Patagonia, there is a surface monitoring of the total ozone concentration which is relevant in the region and constitutes the ozone stations in the southernmost continental regions of the world (excluding Antarctica) (Orte et al. 2020). The long-term monitoring in the region is also essential to evaluate the combination of factors affecting ground UV radiation and to contribute to tropospheric predictability (Damiani et al. 2020).

Although in the future the impact of ODSs will be reduced, as a result of the Montreal Protocol, the effects of this forcing are expected to remain significant during the next several decades (Fang et al. 2019; Pyle et al. 2005). The relative importance of ozone recovery for future Southern Hemisphere climate will depend on the evolution of atmospheric greenhouse gas concentrations (Engel et al. 2018).

Large-Scale Climate Variability Modes and Their Impacts on the Regional Climate

Identifying regional impacts of large-scale circulation changes is not always straightforward as regional climate responds to both large-scale circulation changes and local/regional thermodynamic changes, the latter driven by the energy imbalance and surface warming. However, some studies have identified observed trends in large-scale climate variability patterns that may have affected Patagonian climate.

The SAM has displayed a significant trend toward its positive polarity during the second half of the twentieth century mainly during summer. Several authors have suggested that this trend may be mostly associated with the stratospheric ozone depletion (Thompson and Solomon 2002; Polvani et al. 2011; Thompson et al. 2011; England et al. 2016; Fogt et al. 2017). Moreover, a weakening in the summer trend of the SAM from the last 30 years (Fogt and Marshall 2020) has been associated with the recovering of the stratospheric ozone (Solomon et al. 2016; Engel et al. 2018, and references therein). It has also been discussed that current positive trends of the SAM are a response of both increasing greenhouse gases and stratospheric ozone depletion (Arblaster and Meehl 2006).

Other relevant aspect is the observed change in the PDO polarity around 1976 which arises as one of the most significant drivers of the climatic jump registered in the Southern Hemisphere, manifested in multiple climatic features in South America and particularly as an increase in precipitation over Patagonia (Jaques-Coper and Garreaud 2014; Saurral et al. 2017, among others). Additionally, Saurral et al. (2017) also proposed that the observed trend in the latitudinal extension and strength of the Hadley cell circulation from the 1950s onward may also impact rainfall and winds over Patagonia. They showed that the Hadley cell shifted equatorward during winter over South America, causing a northward shift of the descending branch of this circulation. This shift induces an increase in baroclinicity and hence an increase in precipitation over Patagonia. In summer, an increase in the strength of the subsidence induces an increase of the sea-level pressure at the midlatitudes east of Argentina, which in turn favors enhanced easterly winds and an increase of low-level moisture. Though the two effects have opposite impacts on rainfall, the enhanced low-level moisture overcompensates the increase of the subsidence inducing rainfall increases.

Future Climate Projections in Coastal Areas of Patagonia

Regional Scale

There are several climate change projections based on different climate models ranging from simple ones to complex such as Earth system models. Climate models simulate changes in different variables based on different anthropogenic forcing scenarios. The Intergovernmental Panel on Climate Change reports (IPCC 2014) used in the last climate simulations the RPC (Representative Concentration Pathway) scenarios to conduct the Global Coupled Climate Model simulations in the context of the Intercomparison Project Phase 5 (CMIP5). In addition, a number of experiments were run using regional climate models (RCMs) (i.e., models covering a limited area) which have the advantage of producing simulations with a finer spatial resolution than global models. One of these experiments was the CORDEX (Coordinated Regional Climate Downscaling Experiment) whose aims are achieving a better understanding of regional climate, improving regional models and techniques, and coordinating downscaling experiments around many regions of the world (Giorgi and Gutowski 2015).

In particular, in this section, seasonal changes (summer: December–January–February and winter: June–July–August) in precipitation, temperature, and wind intensity over Patagonia are analyzed using six simulations from the CORDEX with the REMO (Jacob et al. 2012) and RegCM (Giorgi et al. 2012) RCMs. Simulations under the RCP8.5 scenario were used to represent the far future climate (2080–2099). Historical simulations represent present-time climate conditions for the period 1979–2005. Near future (2040–2060) projections are not included in this chapter because they showed a similar pattern of change than that for the far future projections, though with a smaller magnitude. The scenario used in this study to represent the far future climate, the RCP8.5, combines high population growth, low rate of technology development, high energy use, and absence of climate change policies (Riahi et al. 2011). In other words, the RCP8.5 is the worst climate change scenario defined by the IPCC in 2014.

Regarding the projections for the summer mean temperature, positive changes are expected for the entire domain by the end of the twenty-first century with values reaching more than 4 °C in some areas of Patagonia (Fig. 8a). Over coastal areas, changes in temperature for summer range from 2.5 to 3.5 °C are expected. The pattern of temperature change for winter (Fig. 8b) is similar to that for summer: the entire region could suffer an increase in mean temperature of around 3 °C by the end of the twenty-first century for the cold season. In particular, over coastal areas, temperature changes for winter range from 2.5 to 3 °C, with maximum values located near the coastal areas of Santa Cruz province.

Projected changes in precipitation for the far future are evaluated in relative terms (%). Note that for coastal areas of Patagonia, characterized by low annual precipitation amounts, relative changes may be high. Projections indicate positive changes for the northern coastal areas of Patagonia for the summer period (Fig. 8c)

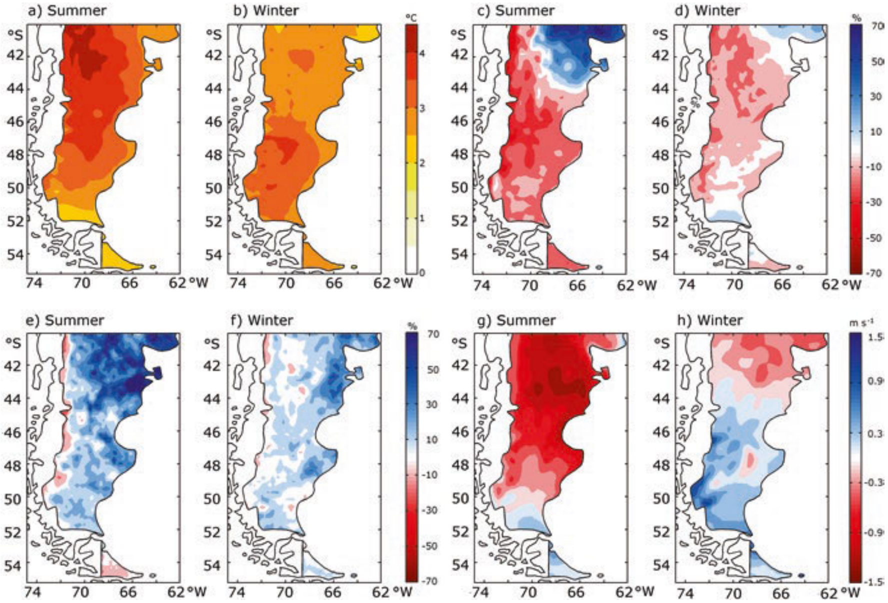

Fig. 8 Seasonal changes of temperature (°C) (**a**, **b**), precipitation (mean (**c**, **d**) and extreme −99th percentile (**e**, **f**)) (%), and (**g**, **h**) wind intensity (m s^{-1}) using an ensemble of regional climate model simulations from the CORDEX database. Simulations under the RCP8.5 scenario were used to represent the far-future climate (2080–2099) regarding present climate (1979–2005) during austral summer (December–January–February) and austral winter (June–July–August). Spatial resolution of 0.22°× 0.22°

by the end of the twenty-first century. Maximum values, up to 60% change for the far future with respect to the present climate, are located in the inland area close to the San Matías gulf. In coastal areas located south of 44°S, projections indicate a decrease in the mean precipitation of around 20% with respect to the present climate. For wintertime (Fig. 8d), far-future projections for the mean precipitation show positive changes over the northern coastal areas (between 20% and 40% with respect to the present climate) and the southern tip of the continent (up to 20%), while a decrease of around 20% in the mean precipitation is expected for the central area of Patagonia by the end of this century. These changes in the precipitation pattern are in agreement with the results found by Pessacg et al. (2020), and it could be associated with the poleward shift of the storm tracks, cyclones, and frontal systems that have been addressed by many authors (Chang et al. 2012; Boisier et al. 2016; Blázquez and Solman 2019, among others) by the end of the twenty-first century. It is important to highlight that the uncertainty in these projections for both summer and winter is very low, since all the individual models present a similar pattern (not shown).

Due to the relevance of extreme precipitation events over continental coastal areas of Patagonia, their changes are also analyzed in this study by calculating the 95th and 99th percentiles, taking into account days with precipitation >1 mm day^{-1}.

For the present climate, summer extreme precipitation maximum values (around 30 mm day^{-1} for the 95th percentile and 50 mm day^{-1} for the 99th percentile) are found over the northern continental coastal areas of Patagonia, while in the rest of the domain, summer extreme precipitation values are around 15 mm day^{-1} for the 95th percentile and 25 mm day^{-1} for the 99th percentile (not shown). For summer, the projections show an increase in extreme events over the entire continental coastal areas of Patagonia (except for Tierra del Fuego province) with maximum values in the northern coastal areas (Río Negro and Chubut provinces), with 60% of increase by the end of the twenty-first century with respect to present climate (Fig. 8e). Wintertime extreme precipitation maximum values for the present climate are found over the north and central of Patagonia, with values around 15 mm day^{-1} for the 95th percentile and 25 mm day^{-1} for the 99th percentile (not shown). Positive changes are expected by the end of the twenty-first century over almost the entire coastal areas of Patagonia (Fig. 8f). The values of the 95th (not shown) and 99th percentiles (Fig. 8f) are higher over the northern coastal areas (around 40% with respect to the present climate), while for the rest of the region, the projected changes are lower than 20%.

Due to the importance of wind in Patagonia, far-future wind intensity projections were also analyzed. Projections for summertime show a decrease in wind intensity over continental coastal areas of Patagonia located north of 50°S, while an increase is expected for the southern tip of the region by the end of this century (Fig. 8g). For wintertime (Fig. 8h), projections for the far future display a pattern of change similar to that of summer but shifted to the north.

In summary, it is highly probable that the continental coastal areas of Patagonia region may suffer an increase of temperature in agreement with previous studies in the region (Barros et al. 2014). Regarding precipitation, the northern part of the region is expected to get wetter (especially in summertime), while the southern area may become drier. The frequency of extreme precipitation events is expected to increase in the entire continental coastal areas, especially over the northern part. Wind projections show a decrease in wind intensity, especially over the northern coast of Patagonia, while over the southern tip of the region, it is projected to increase.

Large-Scale Variability Modes

As previously mentioned, changes in the two main drivers of regional climate change, large-scale circulation and local thermodynamic effects, are not fully independent, and it is difficult to discern how the interplay between these two forcing impacts on regional climate. Nevertheless, given the strong relationships between precipitation variability and some of the large-scale circulation patterns described above, it is expected that for future global warming scenarios, changes either on the strength or the polarity of the main modes of variability affecting Patagonian climate will certainly exert an influence on the future behavior of the regional climate.

This is the case for the projections on the future behavior of the SAM. Future projections of the SAM are strongly controlled by the offsetting influences of the two main drivers of the SAM behavior: the stratospheric ozone recovery effects and the increase in greenhouse gas forcing (Son et al. 2018, and references therein). Based on results from the CMIP5 ensemble, Lim et al. (2016) and Zheng et al. (2014) showed that the SAM will trend toward its positive polarity under strong greenhouse gas forcing (RCP8.5). Moreover, the authors highlight the impact of the positive trend of the SAM on rainfall, which induces a decrease in rainfall over the midlatitudes of the Southern Hemisphere, mainly during summer months. However, the future evolution of the SAM is less certain during the summer season due to potentially offsetting roles of the greenhouse gas forcing and ozone recovery (Arblaster et al. 2011; Fogt and Marshall 2020). Furthermore, under low-emission scenarios, such as the RCP4.5, the competing effects of ozone recovery and greenhouse gases increases largely compensate each other, and the SAM exhibits a nonsignificant trend during the twenty-first century (Zheng et al. 2014). Simpkins and Karpechko (2012) showed that the temporal evolution of SAM indices along the twenty-first century displays large discrepancies depending on how the ozone forcing is prescribed in the models. Furthermore, it is argued that these results may depend on the treatment of the interactive ozone chemistry in the models (Morgenstern 2021), which adds an additional source of uncertainty in the future evolution of the SAM and its impact on regional climate.

Projected changes in the PSA-like modes have been associated with changes in the ENSO forcing. At present, there is no evidence to suggest that ENSO teleconnections in the Southern Hemisphere, the well-known PSA1 pattern, are likely to change under future global warming conditions (Perry et al. 2020). However, projected changes in the ENSO itself, in terms of its amplitude and spatial pattern, may exert an influence on the impact of ENSO. Recent studies based on CMIP5 climate models (Yang et al. 2018, and references therein) have shown that there is a consensus among models in projecting an increase in extreme El Niño and La Niña events in response to global warming. However, there is no consensus on the projected changes in the intensity and frequency of ENSO (Kim and Yu 2012). Nevertheless, climate models tend to agree that under warmer conditions, there will be more Central Pacific El Niño type instead of Eastern Pacific El Niño type (Yang et al. 2018). Even though there is no consensus on the response of ENSO to increased greenhouse gases, the ENSO-related impact associated with a projected increase in frequency of strong El Niño and La Niña events is likely to increase in most regions of South America.

Synthesis and Future Perspectives

Despite the relevance of coastal areas in Patagonia, in particular from an ecological and socioeconomic perspective – which is the focus of this book – not many studies have addressed the effects of climate change on these areas. Results from historical data analysis and model projections by the end of the twenty-first century show clear current trends and future changes for climate variables, climate indexes, and large-scale climatic variability patterns. These changes are affecting coastal areas in Patagonia on short and large timescales, and they will continue and strengthen in the future.

Some of the results presented in this chapter indicate, for example, an increase in extreme precipitation events in coastal areas of Patagonia (stronger in the northern coast). The impacts of this change on coasts on shorter timescales are coastal flooding, coastal erosion, and intense rainfall runoff (Wong et al. 2014). Other relevant results are the trends and future projections for wind intensity, which indicate a reduction in the intensity in the northern coasts and an increase in the southern coasts of Patagonia. These changes affect not only winds but also wave patterns on large timescales in this region (Wong et al. 2014). These changes in the wind intensity could be related to the southern shift of the westerlies that was reported in previous studies (Yin 2005; Villalba et al. 2012), which in turn is probably connected with a higher frequency of SAM-positive phases, both in the last 50 years and in future climate conditions (Zheng et al. 2014; Lim et al. 2016).

To advance in the understanding of the impact of climate change on Patagonian ecosystems, and in the designing and applying adaptation and mitigation measures, it is important to carry out more in-depth studies on climate, climate variability, and climate change focused on regional dynamics at regional and local scales. In coastal areas of Patagonia, sea breeze is an important local phenomenon, and further studies are essential to fully understand its multiple implications for the climate and ecosystems. In addition, there is a lack of studies related to extreme meteorological phenomena in the region, such as droughts, extreme precipitation, temperatures, and wind events. Future projections indicate that this kind of events will continue in the future with increases in magnitude and frequency (Stocker et al. 2013). Moreover, these events affect ecosystems and their services to human beings, and it is highly necessary to study their effects at regional scales.

Finally, further research on large-scale climatic variability patterns and their impact on coastal areas is needed to improve our understanding of the interaction between ecosystems and climate in a context of global change. Assessing and acknowledging the impacts of climate change on coastal areas is critical for a comprehensive understanding of ecosystem vulnerability in this region.

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Physical Changes in the Patagonian Shelf

Martín Saraceno, Jacobo Martín, Diego Moreira, Juan Pablo Pisoni, and Mariano Hernán Tonini

Introduction

The coastal marine regions are expected to be the most vulnerable to the effects of climate change, such as variations in sea level, extreme events, and temperature changes, among others (IPCC 2014). Coastal ecosystems are already affected by the combination of these factors and by the adverse effects of human activities (Oppenheimer et al. 2019). The physical changes observed in the region that extends from the Médanos point (36.9°S) to Tierra del Fuego (55°S) and includes the waters from the coastline to the continental shelf-break are described in this chapter, with particular emphasis in the coastal area. The Patagonian shelf (Fig. 1) can be divided

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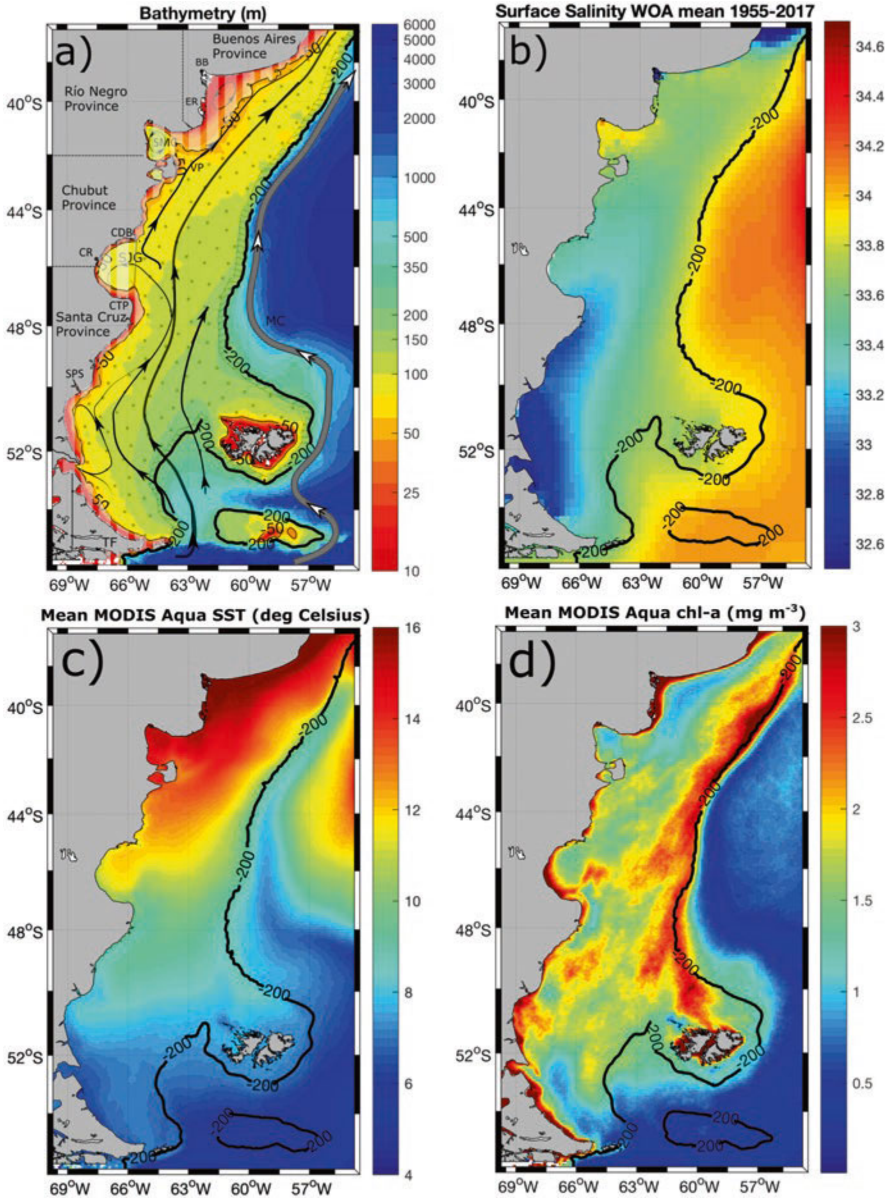

Fig. 1 (**a**) Bathymetry (GEBCO 2020); black thick and thin lines are the 200 m and 50 m isobaths; gray line with white arrows represents the northward Malvinas current; black arrows represent the mean surface circulation over the shelf adapted from Piola et al. (2018); (**b**) Surface salinity from World Ocean Atlas, data collected between 1955 and 2017; (**c**) mean MODIS Aqua SST (degree Celsius) for the period 2002–2020; (**d**) mean MODIS Aqua Chl *a* concentration (mg m^{-3}) for the period 2002–2020. *BB* Bahía Blanca estuary, *ER* El Rincón, *SMG* San Matías gulf, *VP* Valdés península, *CR* Comodoro Rivadavia, *SJG* San Jorge gulf, *CDB* Dos Bahías cape, *CTP* Tres Puntas cape, *MC* Malvinas current, *SPS* southern Patagonian shelf, and *TF* Tierra del Fuego

in three regions from the coast to the open ocean: we define here the inner shelf as the portion of the sea that goes from the coastline up to the 50 m isobath, including all the gulfs and channels; the outer shelf is considered as the 40 km fringe closest to the shelf-break and the middle shelf as the region included between the inner and the outer shelf regions. The inner shelf is characterized by distinct morphological, climatic, and oceanographic features. With more than 3000 km of coasts, the region encompasses four distinct subregions: Buenos Aires shelf, North Patagonian gulfs, San Jorge gulf, and the Southern Patagonian shelf (SPS). The SPS includes the Beagle channel and the Magellan strait. The chapter is organized as follows: data and methods are presented followed by the description of the middle and outer continental shelf, along with the analysis of the observed trends of sea surface temperature, chlorophyll *a* (hereafter Chl *a*), and sea level height. The four subregions are then described individually, followed by highlights of the more relevant results presented.

Data and Methods

To compute long-term physical changes in the ocean, long-term time series of observations are needed. In the Argentine continental shelf, the longest in situ records correspond to sea level observation made by tide gauges (Lanfredi et al. 1998; Santamaria-Aguilar et al. 2017). With data recorded since 1906, the Mar del Plata tide gauge is one of the longest time series of sea level in the world. Yet, apart from the tide gauges' measurements, no long (>10 years) time series are available in the continental shelf, as is mostly the case in the rest of the ocean. On the other hand, satellite altimetry missions offer reliable data of the surface of the ocean that, in some cases, can be longer than 20 years. In particular satellite altimetry represents very accurately sea surface height (SSH) in the region of study (Saraceno et al. 2010; Ruiz Etcheverry et al. 2015, 2016; Strub et al. 2015). Here we compute and analyze sea surface temperature (SST) and Chl *a* concentration for years 2002–2020 and of SSH for years 1993–2020.

In Situ Data

The mean sea surface salinity is retrieved from the World Ocean Atlas (Boyer et al. 2013). This atlas has been constructed with quality controlled in situ observations between 1955 and 2017.

Satellite Data

SST and Chl *a* were obtained from the Oceancolor website (https://oceancolor.gsfc.nasa.gov/, NASA 2018). We used the complete mission (June 2002–May 2020) of monthly maps with 4 km spatial resolution of the two variables. Monthly composites attenuate the instantaneous images but help decrease almost completely the absence of data due to cloudiness. SSH was obtained from Marine Copernicus website (https://resources.marine.copernicus.eu/). We used monthly values of mapped delayed time composites of multiple satellite altimetry missions (product number 008_047) for the period January 1993–December 2020. The spatial resolution of the SSH maps is ¼ of degree.

Numerical Model Output

The output simulations were performed using a numerical model called the Regional Ocean Modelling System (ROMS, Shchepetkin and McWilliams 2005). In the vertical, the primitive equations are discretized over variable topography using stretched terrain-following coordinates. In the horizontal, the primitive equations are evaluated using orthogonal curvilinear coordinates on a staggered Arakawa C-grid. For the vertical mixing parameterization, we selected the scheme developed by Mellor and Yamada (1982). The bathymetry is based on digitized nautical charts. The computational grid has three open boundaries (south, west, and north) where we imposed tidal amplitudes and phases of principal constituents of the region interpolated from a global tidal model (TPXO6, Egbert et al. 1994). We used here two different configurations: one for the north Patagonian gulf region and another for San Jorge gulf domain. For more details in model setup simulations (grid, forcings, open boundaries, etc.), see Tonini and Palma (2017) for the north Patagonian gulfs region and Palma et al. (2020) for San Jorge gulf domain. The rate of tidal energy dissipation was computed as in Tonini and Palma (2017) from the bottom currents field using a bottom drag coefficient of 0.003.

Data Processing

To compute SST and SSH trends, the best fit (in the least square sense) of the sum of annual and semiannual harmonic was subtracted to the original time series at each pixel. Filtering the seasonal cycle from Chl *a* time series is more difficult, as large intra-seasonal and intra-annual variability is present in this variable in the Patagonian shelf (Saraceno et al. 2005). Yet, every year the largest values are observed in the austral spring season (Saraceno et al. 2005; Romero et al. 2006; Andreo et al. 2016). We therefore averaged the monthly values of October, November, and December for every year and computed the trend of the resulting

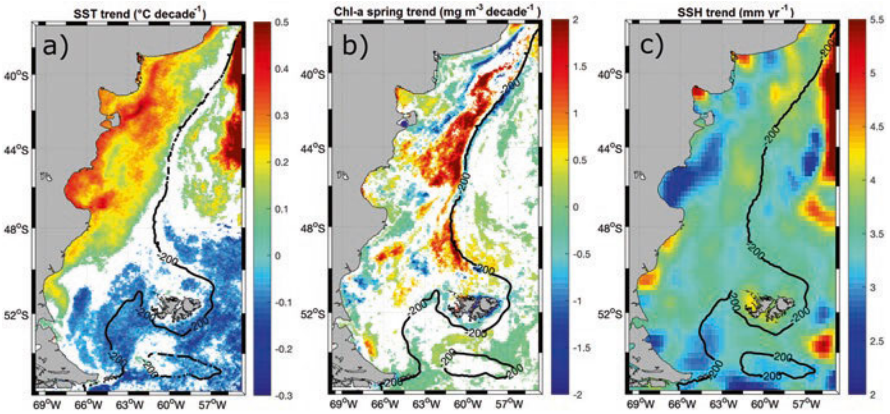

Fig. 2 (**a**) SST trend (°C decade^{-1}); (**b**) austral spring Chl *a* trend (mg m^{-3} decade^{-1}); (**c**) SSH trend (mm yr^{-1}). Both in SST and SSH, the seasonal cycle has been removed. White pixels correspond to nonsignificant (95% confidence level) values

time series at every pixel. The three trend maps obtained are displayed in Fig. 2. Nonsignificant values within the 95% confidence level according to the Student t-test are masked.

Middle and Outer Patagonian Shelf

Baseline

The middle and outer shelf is a wide plateau subject to intense westerly winds and high tidal variability. The outer shelf is bounded offshore by the cold, nutrient-rich, and relatively freshwaters coming from the Antarctic Circumpolar Current. The cold waters flow northward along the Patagonian slope, advected by the Malvinas Current (MC) to about 38°S, where the MC encounters the southward flowing Brazil current and diverges eastward. Both currents form the so-called Brazil/Malvinas Confluence region, through which most of the shelf waters are exported offshore (Franco et al. 2018). The MC is an important barrier for shelf waters (Beron-Vera et al. 2020), though significant intrusions along the shelf-break are observed (Piola et al. 2010). The bathymetry (Fig. 1a) shows that the continental shelf is limited by the 200 m isobath and has a very slow gradient from the coast to the shelf-break.

Continental shelf waters are characterized by relatively freshwaters as compared to the adjacent offshore waters (Fig. 1b). The two main sources of freshened waters are Pacific Ocean-diluted waters and estuarine waters from Río de la Plata. The former enters the Argentinian continental shelf through the Le Maire strait, the southern Patagonian shelf-break and the Magellan strait (Guihou et al. 2020), and produces a particular signature in surface salinity as shelf waters are advected northward by the Patagonian current (Brandhorst et al. 1971). The dilution of the Pacific waters occurs mainly because of the excess of precipitation over the western flank of the southern Andes and due to the seasonal melting of glaciers in southern Patagonia. The second main source of freshwater, the Río de la Plata, drains an average of 22,000 m^3 s^{-1} at about 34.5°S through the widest estuary in southern South America. Most of the Río de la Plata outflow is advected northward to the Uruguay and southern Brazilian shelves forced by the dominant winds (Piola et al. 2005; Saraceno et al. 2014). Southwesterly winds can advect Río de la Plata freshwaters southward up to 38°S along the coast of the Buenos Aires province, particularly in austral summer (Piola et al. 2018). The combined discharge from all rivers along the Patagonian coast are an order of magnitude lower than the Río de la Plata input of freshwaters and have been reported to have only a local influence, as is discussed below. The unique distinctive source of waters saltier than the mid-shelf waters is the San Matías gulf (SMG) (Fig. 1b). As detailed in the North Patagonian Gulfs Section, SMG has a closed circulation in austral summer which, together with the fact that net evaporation is larger than precipitation during that season, makes the SMG an important source of saltier water. Saltier water produced in the SMG exits the gulf through the northern portion of the mouth and is advected toward the north over the continental shelf, mainly during austral autumn (Lucas et al. 2005; Tonini et al. 2013).

The mean SST (Fig. 1c) shows that the largest values are located close to the coast, along the Buenos Aires and Río Negro provinces and that a marked negative gradient toward the South is only interrupted by the signature of the MC. Indeed, the MC advects the cold sub-Antarctic waters up to about 40°S and clearly affects the SST along its path (Saraceno et al. 2004).

Finally, mean Chl *a* (Fig. 1d) shows that the largest values are observed along the upper portion of the Patagonian slope and adjacent outer shelf region as well as all along the coast. Chl *a* concentrations along the coast (Fig. 1d) might be associated with the stimulation of phytoplankton growth by the inflow of riverine nutrients but are also very likely biased by dissolved organic matter of terrestrial origin and resuspension caused by tidal mixing (see Villafañe et al. this volume).

The large values along the shelf-break and in the outermost portion of the continental shelf are sustained by the upwelling of the nutrient-rich MC waters over the upper portion of the slope. The mechanism responsible for such upwelling has not been proven yet, but several hypotheses based on observational evidence and numerical models have been proposed. The main hypotheses are the divergence of the MC (Matano and Palma 2008), the divergence produced by wind stress curl (Saraceno et al. 2005; Carranza et al. 2017) and the passage of coastal-trapped waves (Acha et al. 2004; Saraceno et al. 2005; Poli et al. 2020). In the mid-shelf, the largest Chl *a* concentrations are associated with tidal fronts (Acha et al. 2004; Romero et al. 2006).

Observed and Expected Changes

Figure 2a shows that SST marks a significant positive trend (up to 0.04 °C per year) north of ~50°S, while negative values (up to −0.02 °C per year) are observed south of 50°S. Similar results were observed in Leyba et al. (2019) using Reynolds et al. (2007) SST data for the period 1982–2015. Leyba et al. (2019) also highlighted that the SST trend in the region is strongly linked to trends in heat fluxes. The negative SST trend observed in the southern portion of the region is associated with the positive trend observed in the dominant westerly winds within those latitudes (Marshall 2003). Stronger westerlies favor the entrance of colder offshore waters via a larger Ekman transport. The spring Chl *a* linear trend observed in Fig. 2b shows values as large as 2 mg m^{-3} over a 10-year period in the outer portion of the continental shelf between 50 and 40°S. Marrari et al. (2017) produced a 20-year (1997–2017) time series merging SeaWiFS and MODIS Aqua data and analyzed the total Chl *a* trend around South America. They found an order of magnitude smaller values as compared to what is shown in Fig. 2b. However, results are not comparable because (i) we considered only austral spring months and Marrari et al. (2017) used all-year-round months and (ii) the period considered in the two studies is not the same. The mechanisms that might explain the large Chl *a* trends observed should be investigated.

The linear trend in SSH (Fig. 2c) ranges between 2 and 5 mm yr^{-1} (95% confidence level) in good agreement with Ruiz Etcheverry et al. (2016). In the northern region, the positive linear trends are associated with local changes in the density field caused by advective effects in response to a southward displacement of the South Atlantic High (Ruiz Etcheverry et al. 2016).

The continental shelf circulation is also affected by important interannual variability that mostly has its origin in the variability of the wind. In continental shelves, the alongshore component of both wind and ocean currents is the dominant one (Gill 1982). Using in situ and satellite altimetry as well as the time series of the SSH obtained from the tide gauge at Mar del Plata, Lago et al. (2021) showed that the alongshore component of the interannual variability of the transport in the northern portion of the shelf (at about 38°S) is significantly correlated with the Southern Annular Mode (SAM). This happens thanks to the geostrophic adjustment that occurs when the wind is parallel to the coast (Gill 1982). The same conclusion, i.e., that SAM explains a large portion of the interannual variability of the currents in the Patagonian shelf, was obtained using regional numerical models in the southern portion of the shelf by Combes and Matano (2018) and Guihou et al. (2020) and, using a global reanalysis model, by Bodnariuk et al. (2021a, b).

Findings reported here are in agreement with the increase in water temperature and sea level reported in the framework of the latest Intergovernmental Panel on Climate Change (IPCC) report for the southwestern Atlantic (Bindoff et al. 2013). The statistical confidence is quantified as low, moderate, or high in the IPCC report. The water temperature increase and sea level have a moderate confidence in the region (Bindoff et al. 2013). A decrease in dissolved oxygen concentration (low confidence) and in pH, increasing ocean acidification (high confidence), are also predicted (Bindoff et al. 2013). In the Southern Hemisphere, the SAM influences the zonal asymmetry in the westerly winds and generates convergent and divergent transport in the Antarctic Circumpolar Current. In turn, the wind-driven currents in the Antarctic Circumpolar Current contribute to the regional asymmetry of decadal sea level variations during most of the twentieth century (IPCC 2014; Thompson and Mitchum 2014). Net regional sea level changes were estimated by the IPCC (2014) from a combination of the various contributions to sea level change (dynamic sea level, atmospheric loading, glacier mass changes, and ice sheet surface mass balance) derived from CMIP5 climate model outputs either directly or through downscaling techniques (Perrette et al. 2013; Kopp et al. 2014; Slangen et al. 2014; Bilbao et al. 2015; Carson et al. 2016). The contributions from groundwater depletion, reservoir storage, and dynamic ice sheet mass changes were not simulated by coupled climate models over the twentieth century and were estimated from observations. The sum of all contributions, including the glacio-isostatic adjustment contribution, provided a modelled estimate of the twentieth century net regional sea level changes that shows, for the Patagonian region, an increase that ranges between 100 and 200 mm in relative sea level (IPCC 2014).

Inner Shelf

Buenos Aires Coastal Waters

Baseline

The coastline of the Buenos Aires province is very extensive: it goes from the Rasa point (36.3°S), the exterior southern limit of the Río de la Plata estuary, to the mouth of the Negro river (41°S). The coastline can be divided in a northern and southern section, being Bahía Blanca (Fig. 3) the division point. In the northern section, there are a large number of beaches that are used for tourist and recreational purposes during the summer season and a series of cliffs that are being affected by erosion. The ports of Quequén and Mar del Plata are also in the northern region, the latter with serious sediment deposition problems. The southern section is known as El Rincón area and includes the Anegada bay (Fig. 3). El Rincón area is of great importance for the Patagonian Sea due to the exchange of water masses that occur in it and with the surrounding coastal areas. Inlets, marshes, tidal flats, and different types of beaches can be identified throughout the El Rincón region that is also strongly influenced by the continental discharge of the Colorado and Negro rivers. South of Anegada bay, the coast presents sandy beaches with little slope. The whole region is socially and economically important (see Narvarte et al. this volume). El Rincón area is a rich region for fishery production (Rodrigues et al. 2013; Jaureguizar et al. 2016), and the estuary of Bahía Blanca contains one of the most important industrial ports in Argentina. In both areas very large wetlands rich in flora and fauna must be protected and conserved to preserve the natural ecosystem that sustains fisheries and

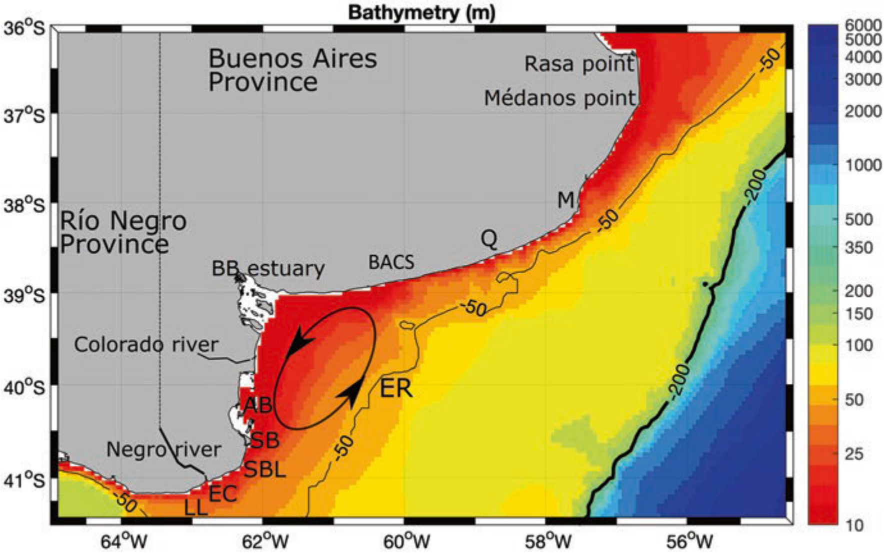

Fig. 3 Bathymetry (GEBCO 2020) for the Buenos Aires coastal waters; black thick and thin lines are the 200 and 50 m isobaths; geographical locations indicated are *BACS* Buenos Aires coastal shore, *M* Mar del Plata, *Q* Quequén, *BB* Bahía Blanca, *ER* El Rincón, *AB* Anegada bay, *SB* San Blas bay, *SBL* Segunda Barranca lighthouse, *EC* El Cóndor, and *LL* La Lobería (Bermeja point)

recreational activities and provides intangible well-being to the society. Yet, large changes, both of anthropogenic and natural origins, are registered in the region.

The circulation in the region is dominated by the alongshore component of the wind and by the tides (Palma et al. 2004; Lago et al. 2019, 2021). The largest changes in ocean circulation in this region are associated with atmospheric circulation which is dominated by the presence of the semipermanent South Atlantic anticyclone, centered approximately at 30°S. The tidal regime is predominantly semidiurnal, and the mean range increases along the coast, from 1.7 m at San Blas bay to 3 m at El Cóndor (SHN 2018).

One of the physical phenomena that most affects the coasts are waves. Wörner et al. (2019) reported that at the south of Bahía Blanca estuary, the waves that propagate from the southwest, west, northwest, north, and from the northeast are significantly more frequent than the waves coming from the south and southeast. The mean wave heights increase southward, from 0.72 m at Anegada bay to 1.26 m at Segunda Barranca lighthouse, and decrease south westward, reaching 0.48 m in front of La Lobería (Bermeja point). This would provide a higher percentage of southward and south-westward longshore currents.

The waters in the El Rincón area can be divided in two: (i) the coastal ones influenced by the river discharge and (ii) the waters influenced by the advection of shelf waters coming from the south and from the SMG (Guerrero 1998; Lucas et al. 2005). The estuarine system is formed by the Negro and Colorado rivers that discharge, on average, 950 m^3s^{-1} and 150 m^3s^{-1}, respectively, (BDHI 2020; COIRCO

2020) and have a seasonal variability (Lucas et al. 2005). The El Rincón estuarine system varies its area between 10,000 km^2 during the austral autumn-winter period and about 15,000 km^2 during austral spring-summer (Lucas et al. 2005). Lucas et al. (2005) indicate that the river discharge produces a low-salinity area strongly affected by the water masses that come from the SMG with high salinity, which generates a strong salinity gradient with low values near the coast. The surface fields show a maximum salinity gradient following the 40–50 m isobath (Lucas et al. 2005). The circulation of the El Rincón water masses presents an anticyclonic gyre during spring and summer and is more constrained to inshore areas during winter.

Reiter et al. (2019) explored the seasonal variability of temperature and salinity in the El Rincón area. During the austral winter, temperatures near the surface range from 8 to 10 °C in the coastal region and between 6 and 8 °C in the middle shelf. Near the bottom, winter waters along the coast are warmer (12 °C), while surface and bottom temperatures are similar (6 to 8 °C) in the middle shelf, indicating the importance of the vertical mixing process there. Winter salinity field shows minimum values (lower than 33) near the coast due to the larger discharge of freshwaters from the Negro and Colorado rivers. Winter salinity maps show a marked gradient toward the East, up to the 40–50 m isobath, where salinity is 34 due to the influence of the SMG water plume (Guerrero et al. 1997; Lucas et al. 2005). Further east, winter salinity decreases to 33.5. In spring, surface temperature increases up to 16 °C near the coast; river discharge is maximum, affecting the salinity field near the coast; and the salty waters from the SMG spread along the coastal strip up to the 40–50 m isobath. During summer, temperature in the El Rincón area is distributed homogeneously in the vertical, with large values (20 °C) from the coast up to the 50 m isobath, where a well-marked gradient is observed. The influence of the SMG high-salinity (34) waters is also observed in summer. Finally, in autumn, temperature decreases to 14–16 °C near the coast, the SMG water plume is clearly visible (with larger temperatures), and the vertical homogeneity and the horizontal gradient observed in summer remain. Salinity reaches the maximum values in the Bahía Blanca estuary region (up to 35) and minima (32) in the Anegada bay.

Observed Changes

Satellite altimetry results for the 1997–2017 period (Fig. 2c) suggest that the SSH trend goes from 3 mm yr^{-1} in El Rincón region up to 4.5 mm yr^{-1} in Bahía Blanca estuary, and between 3 and 4 mm yr^{-1} to the north of that site. The IPCC (2014) determined that the interaction of sea-level rise and changes in precipitation will have a more severe impact on shallow estuaries (<10 m) than on deep basin estuaries (>10 m) (Hallett et al. 2018; Elliott et al. 2019).

The IPCC Fifth Assessment Report confirms that the ocean is getting progressively warmer, with parallel changes in ocean chemistry such as in acidification and oxygen loss (Rhein et al. 2013). In the northern Patagonian region, the increase of the SST can be confirmed by the MODIS observations (Fig. 2a) with a positive trend of 0.2 °C decade^{-1} for the coastal region of El Rincón (up to 40–50 m isobath) and a positive trend of 0.4 °C decade^{-1} toward the east. On the other hand, bottom temperatures do not show a significant trend at El Rincón for the period 1980–2016 (Elisio et al. 2020). Temperatures at El Rincón also show an irregular oscillation with periodicities between 3 and 7 years that could be in part due to the biennial and intra-decadal periodicities related to the high (2–4 years) and low (5–7 years) frequency components of the El Niño-southern oscillation variability (Guerrero 1998; Penland et al. 2013; Reiter et al. 2019; Elisio et al. 2020).

Finally, Pérez et al. (2017) found significant positive trends in wind waves near Mar del Plata, reaching maximum values of 16 mm per decade. Trends in the significant wave height were statistically different from zero only for the east and northeast directions. Negative trends (significantly different from zero, with 95% confidence) were obtained for waves coming from the southwest (Pérez et al. 2017). Echevarría et al. (2019) observed that the alongshore wave energy flux from Bahía Blanca estuary to Mar del Plata is related to the natural erosive and constructive processes detected.

North Patagonian Gulfs

Baseline

This section analyses the circulation of the North Patagonian gulfs, a region of the Argentinean Sea that is located between 40 and 43°S and includes the SMG, Nuevo gulf (NG), San José gulf (SJOG), and the Valdés peninsula (Fig. 4). The region constitutes one of the most important marine ecosystems in the Argentine Sea. Both the reservoir of coastal flora and fauna and the fishing resources (commercial and artisanal) have captured the attention and financial support of international organizations linked to the conservation and care of the environment. Also, the region has long been recognized for the high productivity and biodiversity of the ecosystem (Acha et al. 2004).

As in the rest of the continental shelf, in situ observations are scarce. In particular, current records are few and of short duration (Framiñan et al. 1991; Rivas 1997; Moreira et al. 2009; Saraceno et al. 2020) and mostly show that the region is dominated by high-frequency, inertial fluctuations and tides. The shortness of the time series is inadequate to reveal the mean circulation. For this reason, the average circulation in the area is mainly inferred from hydrographic data, biological indicators, and numerical models.

The geometry of the mouths of the three gulfs hampers the renewal of the waters inside of them. Therefore, waters within the gulfs are largely influenced by the local atmospheric forcing (Rivas 1990). While the surface heat flux changes direction throughout the year, the freshwater flow is always toward the atmosphere, since evaporation exceeds precipitation (Scasso and Piola 1988). These characteristics of the atmospheric flow and the limited renewal of its waters produce a greater annual thermal amplitude and relative maxima of salinity within the gulfs (Lucas et al.

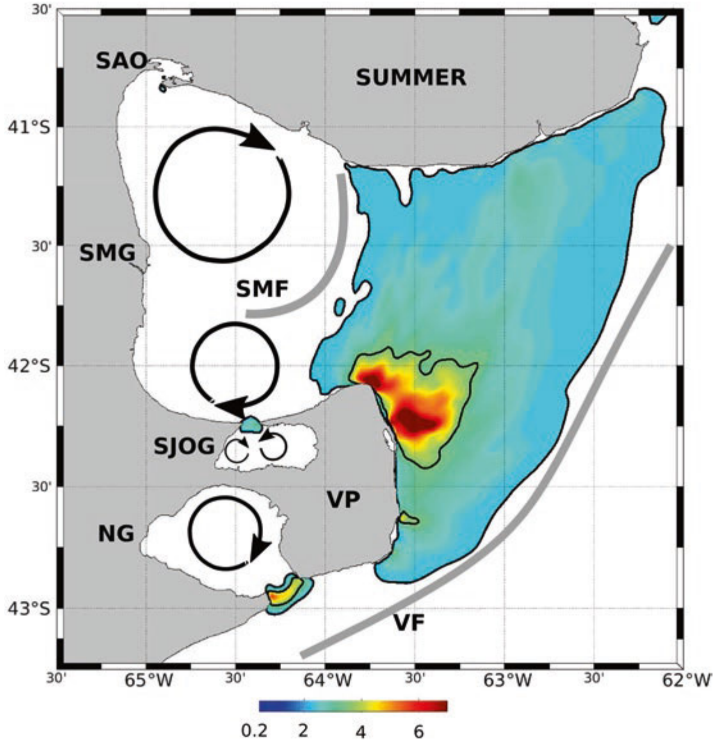

Fig. 4 Summer main features of North Patagonian gulfs. Background colors represent the tidal energy dissipation of the principal tidal constituent M2 [W m^{-2}]. The solid gray line indicates schematic locations of the thermal fronts (*SMF* San Matías front, and *VF* Valdés front), and the black solid line represents the main gyres into the gulfs. *SAO* San Antonio Oeste, *SMG* San Matías gulf, *SJOG* San José gulf, *NG* Nuevo gulf, and *VP* Valdés peninsula. (Adapted from Tonini and Palma 2017)

2005; Tonini et al. 2013). As noted in the previous section, the drainage of the relatively saline waters of the SMG through the north of the mouth invades the El Rincón estuary sector during winter (Lucas et al. 2005; Tonini et al. 2013). The main entrance of colder and less saline waters is through the southern sector of the mouth of the SMG (Rivas and Beier 1990).

The whole region is characterized by intense westerly winds and significant surface heat and freshwater fluxes (Scasso and Piola 1988), as well as a great amplitude of tides (Palma et al. 2004). Tides reach more than 9 m of maximum amplitude range inside SMG, at San Antonio Oeste (Fig. 4), 8 m in SJOG, 6 m in the NG, and over the Punta Norte-Valdés peninsula (SHN 2018). The bottom topography and the complex coastline are such that there is a phase shift of nearly a half period on both sides of the 7-km-long isthmus that separates NG from SJOG. This peculiarity, together with the large amplitude of the tides, has promoted the interest for the generation of tidal energy (Palma 2002). The interaction of the large tidal currents with

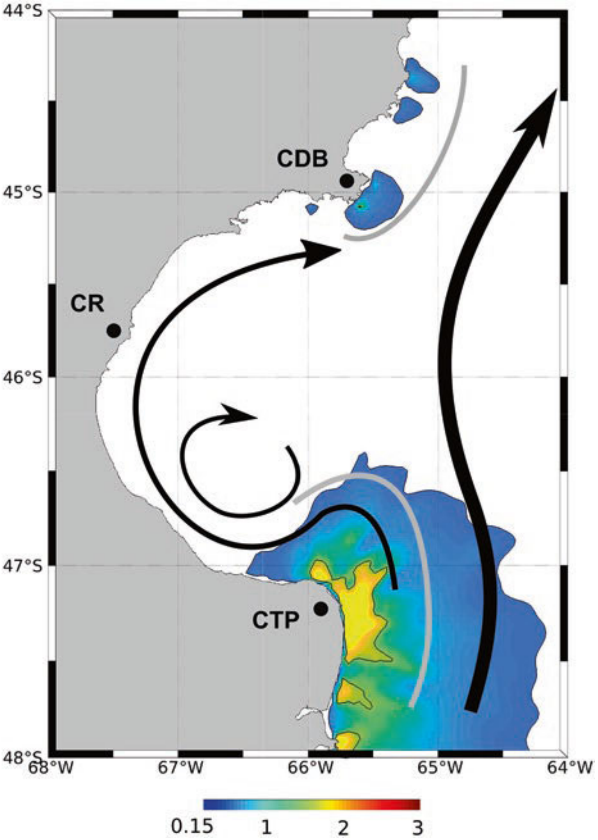

Fig. 5 Main features of San Jorge gulf. Background colors represent the tidal energy dissipation of the principal tidal constituent M2 [W m^{-2}]. The solid gray lines indicate schematic locations of the thermal fronts, and the black solid lines represent the main summer circulation. *CDB* Dos Bahías cape, *CR* Comodoro Rivadavia, and *CTP* Tres Puntas cape. (Adapted from Palma et al. 2020)

the complex irregular bottom topography produces in the region one of the highest energy dissipation rates of the South Atlantic ocean (Fig. 5; Palma et al. 2004). The latest numerical simulations in the region (Tonini and Palma 2017) improved its accuracy, thanks to several in situ measurements: a 22-month time series of bottom pressure measurements that was obtained close to the northern coast of the SMG (Lago et al. 2017) and other four coastal stations where current-meter measurements were obtained (Moreira et al. 2011). The authors showed that the total area-integrated energy tidal dissipation attains 27.9 GW. This result is larger than the one calculated by Moreira et al. (2011) and is in close correspondence with the 28 GW computed by Palma et al. (2004). The value represents ~24% of the total energy dissipated in the Southwestern Atlantic shelf (Palma et al. 2004). The vertical mixing induced by the tidal energy in combination with the increased heat fluxes in spring and summer allows the homogenization of the water column in shallow areas and the occurrence of thermal fronts that separate these well-mixed waters from the stratified waters. Indeed, one of the most important frontal zones of the Argentine shelf is the Valdés front (VF, Fig. 4), located near Valdés peninsula in a SW-NE direction (Fig. 4) (Glorioso 1987; Romero et al. 2006). Also, near the mouth of the SMG, a thermal front (SMF, Fig. 4) delimits the internal circulation of the gulf from external waters (Gagliardini and Rivas 2004; Tonini et al. 2013; Pisoni et al. 2015). Associated with the dynamics of these frontal systems, there is a high rate of primary and secondary productivities that constitute key ocean structures to understand the feeding, reproduction, and migratory patterns of local populations of birds and mammals, as well as important fishing resources (Sabatini and Martos 2002; Acha et al. 2004).

The latest advances in the dynamical knowledge of the region were provided from numerical simulations (Tonini et al. 2013; Tonini and Palma 2017). One of the main results is that tidal forcing, stratification, and winds significantly contribute to the overall subtidal residual circulation of the region. The model shows that the nonlinear interaction between the oscillating tide and bottom topography leads to the formation of several robust residual circulation patterns, basin gyres, bathymetric vortices, and coastline quadrupoles, which are formed by recirculating eddies at the mouths of SJOG and NG. The results of the numerical simulations also show inside SMG that the overall summer circulation pattern is dominated by a strong cyclonic gyre (composed by two recirculating sub-gyres) (Fig. 4). As a result of this closed circulation, the gulf is almost isolated from the shelf during summer. The location and direction of circulation of the gyres of the SMG were advanced by means of an analysis of hydrographic data by Piola and Scasso (1988) and partially confirmed by direct measurements in a station near the north gyre by Framiñan et al. (1991). Although the velocities provided by the numerical model (ROMS, Tonini et al. 2013) show the correct temporal direction and intensification, they are somewhat lower than the measurements (~15 cm s^{-1} on average) and require a greater number of long-term direct measurements (currents) to allow calibration and validate the results. The summer circulation pattern was validated for the first time by the trajectory of five drifters deployed in the northern sector of the SMG (Saraceno et al. 2020). The drifters also showed the presence of small-scale features that are not observed with the climatological forced models. In particular, a strong filament that detaches from the western coast and advects coastal waters to the middle of the gulf was observed with both the drifters and high-resolution satellite color images (Saraceno et al. 2020). Within the coastal jet, nontidal currents can be as large as 21 cm s^{-1}. Similar velocities have been observed closer to the coast with current-meter measurements (Moreira et al. 2009).

The numerical model results of the same authors also show that in winter, when the stratification is eroded and the northern sub-gyre spins down and gradually shrinks in size, the western sector of the gulf is occupied by an anticyclonic gyre. The wind forcing strengthens both the cyclonic and anticyclonic circulation during fall-winter.

In the NG the dynamics is similar to the one observed in the SMG. However, in the NG there is only 1 year-round cyclonic gyre (Fig. 4) that intensifies in summer and is reduced in spatial extension in winter, with the appearance of a weak anticyclonic gyre in the western coast. The cyclonic gyre of NG was observed remotely from optical and thermal channels of the Landsat-TM (Gagliardini 2011), and in both gulfs (NG and SMG), vertical profiles show a dome shape of the isopycnals in the center of the gulfs, indicative of a cyclonic circulation (Pisoni 2012; Tonini et al. 2013).

The SJOG (Fig. 4) has a very different seasonal behavior. In summer, it can be separated in two domains with different dynamics and thermal characteristics: the western domain is more affected by strong tidal currents than the eastern domain. As a consequence, waters are warmer on the surface, and vertical stratification is set up in the eastern domain during summer. In winter, the entire gulf is vertically homogeneous (Esteves et al. 1986). Using satellite remote sensing data, Amoroso and Gagliardini (2010) observed vortices and jets in the western domain of the SJOG and in the south of the SMG. These patterns are generated by the exchange of waters between the SJOG and SMG and are clearly visible also in high-resolution numerical simulations (Tonini and Palma 2017).

Observed Changes

Satellite altimetry measurements show a trend of the SSH of up to 4.6 mm yr^{-1} in the northwest coast of SMG and of about 3 mm yr^{-1} in NG (Fig. 2; Ruiz Etcheverry et al. 2016). Values at San Antonio Oeste are among the largest in the entire Argentine shelf. Yet, given the large tidal amplitude in this region (see above) and the vicinity of the coast that affects satellite altimetry measurements, results should be interpreted with care.

Given the southward migration of the semipermanent South Atlantic high-pressure system (Barros et al. 2008; Blázquez et al. 2012), a higher frequency of northerly winds can be expected over this region of the Patagonian coast. This scenario could favor the occurrence of coastal upwelling events described in Pisoni et al. (2014). On the other hand, a decrease in the mixed-layer depth (5 m per decade) was estimated by a global numerical model in the SMG and NG according to Franco et al. (2018) between 2003 and 2017. This change should have strongly affected the summer circulation, the transport of the main gyres, and the local ecosystem. Yet, evidence of such changes based on observations have not been reported so far.

Despite the absence of published works related to the climatic effects on the circulation and dynamics of the north Patagonian gulfs, numerical models could be one of the keys to explore possible future scenarios at low cost based on the trending physical variables shown by satellite or studies in other regions of the world. The region of the north Patagonian gulfs remains largely an unexplored region, especially in terms of in situ observations. The studies carried out lack precision due to the scarce direct measurement of physical variables. With the help of tools such as numerical models and satellite images, large spatial and temporal gaps are covered that help to understand the dynamics of the region and thus predict future changes.

San Jorge Gulf

Baseline

San Jorge gulf (SJG) constitutes a complex ecosystem that provides a variety of important services to the regional economy, as oil (Sylwan 2001), fisheries (Glembocki et al. 2015; Temperoni et al. 2018), and tourism (St-Onge and Ferreyra 2018). At the same time, the gulf constitutes one of the regions with the greatest biodiversity of the Patagonian shelf (see chapters by Galván et al. this volume and Crespo this volume).

The SJG is the largest gulf of the Patagonian coast of Argentina. With an extension of nearly 40,000 km^2, it is located between Dos Bahías and Tres Puntas capes (Fig. 5). The center of the basin is deeper than 100 m. The gulf mouth extends for approximately 250 km, with shallower depths at the southern end (Fig. 5).

There are no rivers that flow into the gulf, and evaporation exceeds precipitation in the whole area (ECMWF ERA-40 Atlas, https://sites.ecmwf.int/era/40-atlas/docs/section_B/parameter_emp.html). The Patagonian region is influenced by mid-latitude westerlies, which are strongest in the latitude of this gulf (Labraga 1994). Tides are semidiurnal, with a mean amplitude of 4.18 m in Comodoro Rivadavia (the main city on the gulf coast, Fig. 5) and a maximum of 6.09 m (SHN 2018). The bottom friction produced by the interaction of the tidal currents and shallow banks located near Tres Puntas cape produces one of the largest tidal dissipation areas of the Patagonian shelf (Palma et al. 2004; Moreira et al. 2011).

SJG waters are a mixture of waters of subantarctic origin, modified by air-sea heat fluxes and low-salinity waters from the South, advected by the Patagonian current (Brandhorst et al. 1971; Palma and Matano 2012). During summer, the pycnocline reaches 40–50 m depths, deepening to exceed 60 m in autumn (Cucchi-Colleoni and Carreto 2001). Intrusions of low-salinity waters from the Patagonia current at intermediate depths have been reported in autumn (Krock et al. 2015) and summer (Carbajal et al. 2018).

The vertical structure is homogeneous in winter and stratified during summer in much of the gulf (Torres et al. 2018). The summer pycnocline, approximately matching the depth of the euphotic zone, separates surface nutrient-poor, oxygen-rich waters from deeper nutrient-rich, oxygen-poor waters (Torres et al. 2018). In the north and south of the gulf mouth, the water column remains vertically homogeneous even in summer due to tidal mixing with high dissipation rates (Fig. 5; Palma et al. 2004), favoring the generation of tidal fronts (Acha et al. 2004; Rivas and Pisoni 2010; Glembocki et al. 2015; Carbajal et al. 2018; Flores-Melo et al. 2018). Carbajal et al. (2018) have found variations in the position of the tidal front of approximately 8 km near spring tide and 4 km prior to neap tide, although baroclinic instabilities can significantly modify the shape and position of the front (Carbajal et al. 2018; Flores-Melo et al. 2018). Furthermore, the authors have found great variability in Chl *a* concentrations between both tidal phases, suggesting a greater intrusion of subsurface waters during neap tide.

As current velocity data are scarce within the SJG, up-to-date knowledge on gulf dynamics is based mainly on the outputs of numerical simulations. Recently, Matano and Palma (2018) and Palma et al. (2020) described the seasonal circulation in SJG. During summer, an inner portion of the Patagonian current enters the SJG, generating a loop that merges with an intense cyclonic coastal current (Fig. 5). The loop and the coastal current enclose a recirculating cyclonic gyre in the southern basin. In the northern sector, a weak and elongated anticyclonic coastal gyre is developed, while the interior circulation is composed of a slow anticyclonic gyre bounded in the west by the coastal current and by a broad northward flowing current in the east. These two currents encounter before exiting the SJG as an intense jet through its northern edge (Dos Bahías cape). From late fall to early winter, the Patagonian current moves offshore, thus reducing its penetration into the gulf. During winter, the cyclonic coastal current and the southern gyre weaken, and anticyclonic patterns are developed in the southern region. Furthermore, the southeast anticyclonic gyre expands, blocking a large portion of the mouth, thus shifting the inflow of Patagonian shelf waters to the north. Increasing stratification during spring leads to an intensification and expansion of the cyclonic circulation, and, by the end of December, the summer circulation pattern is fully developed. Superimposed on these seasonal circulation patterns, there is an anticyclonic gyre over the southern bank that persists year-round. The largest exchange with the shelf occurs in summer, mainly at the surface and at intermediate layers and confined to the northern region. Then, waters are replaced with waters mostly coming from the Patagonian current (Palma et al. 2020).

There are very few measurements of currents in the gulf. Mean velocities from three drifting buoys deployed near Comodoro Rivadavia city ranged between 0.27 and 0.38 m s^{-1}, with maxima of ±1.50 m.s^{-1} inside the SJG (Esteves et al. 2012). During November 2017, reversal velocities near 0.4 m s^{-1} associated to tidal currents were registered in the northern region close to the mouth, with maxima that exceeded 1 m s^{-1} (Pisoni et al. 2020). In March 2020, maximum velocities of approximately 0.5 m s^{-1} were detected in a shallow region (< 30 m) in the north of SJG.

Observed Changes

As well as tidal mixing, coastal upwelling is also a mechanism that favors the ascent of nutrients from deeper layers. Although westerly winds on the east coast of Patagonia are not favorable to upwelling (Matano et al. 2010), given the semicircular shape of the SJG, favorable conditions can be generated on the southern coast of the gulf (Tonini et al. 2006; Pisoni et al. 2020). It is expected that an increase in the intensity of the westerlies (Thompson et al. 2011) will have an impact on the coastal upwelling (see however Pessacg et al. this volume). In addition, another mechanism for input of nutrients into the sea is due to the contribution of dust transported by the atmosphere. In the Patagonian shelf, dust contribution to primary productivity is a subject of active research: Johnson et al. (2011) concluded that atmospheric fluxes of mineral dust from Patagonia are not likely to be the major source of bioavailable iron to ocean regions characterized by high primary productivity; similarly, a recent study that combined a long record of in situ terrestrial dust, satellite data of Chl *a* and currents suggested that dust from Tierra del Fuego is not a source of nutrients for the Chl *a* blooms observed (Cosentino et al. 2020). On the other hand, Paparazzo et al. (2018) observed a bloom after a dust event in the NG coastal area. In a context of intensification of the westerly winds, dust storms could favor the fertilization of the ocean if its role as a fertilizer is confirmed in the area.

A positive trend in SST of about 0.3 °C per decade is shown in Fig. 2a. Recently, Leyba et al. (2019) found a significant positive trend in SST during winter over much of SJG, not being significant in summer. On the other hand, the sea level anomaly trend found within SJG is one of the smallest ones along the Patagonian coast (Fig. 2c; Ruiz Etcheverry et al. 2016).

Finally, Marrari et al. (2016) found an increase of 2% per year of Chl *a* concentration within the SJG since 1997. This positive trend is mainly located in the coastal regions (depth < 50 m) west and south of the GSJ (Fig. 2b; Marrari et al. 2016).

The Southern Patagonia Shelf, Beagle Channel, and Magellan Strait

Baseline

The properties and dynamics of the water masses present in the southern Patagonian shelf (SPS) and associated channels and straits south of 47°S are largely influenced by the inflow of diluted subantarctic waters coming from the Pacific ocean. This connection is provided by the eastward outflow of the Magellan strait (Brun et al. 2020) and the Cape Horn current (Strub et al. 2019), a branch of the West Wind Drift that flows poleward along the Pacific coast of South America from 40°S. Upon encountering Cape Horn, the waters transported by the Cape Horn current are advected northeastward by another branch of the Antarctic Circumpolar current and enter the SPS through the Le Maire strait and the passage east of Isla de los Estados (Guihou et al. 2020; see Fig. 6 for geographical locations).

The precipitation regime in the Magallanes-Tierra del Fuego region exhibits a distinct longitudinal gradient, with a sharp discontinuity marked by the Andes mountain range. Humidity from the Pacific ocean is pushed by the prevailing westerlies, which produces high precipitation rates by orographic control on the western side of the Andes. On the contrary, dry winds and relatively low precipitations are a common feature east of the cordillera. Together with direct rainfall, seasonal (spring-summer) inputs from snow and ice melting also contribute to freshwater

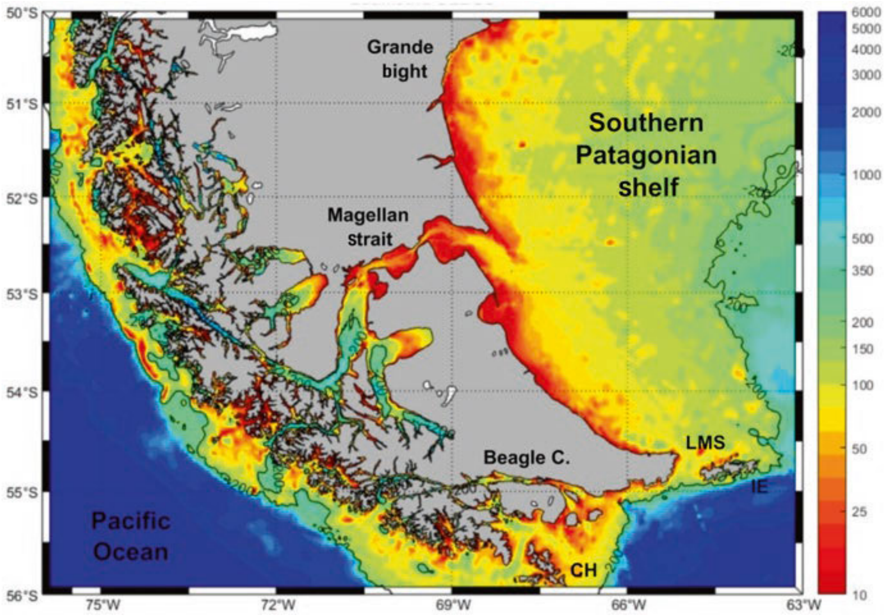

Fig. 6 Bathymetric chart (depth in meters) of the southern Patagonian shelf. CH, LMS, and IE correspond to Cape Horn, Le Maire strait, and Isla de los Estados, respectively

inputs. The precipitation/runoff excess on the Pacific side results in a significant dilution of subantarctic waters in the southeastern Pacific, a signal that, helped by the regional circulation, propagates to the Patagonian shelf and can be traced as far north as SJG (Acha et al. 2004) or even the SMG according to Palma and Matano (2012). The northeastward flow of waters of Pacific origin has been estimated as 0.88 Sv at 51°S by Guihou et al. (2020).

The west coast of the Andes presents a complex morphology inherited from the combined action of tectonic movements and successive glaciations during the Quaternary (Rabassa and Clapperton 1990; Rabassa 2008; see Isla and Isla this volume). These cycles have carved a vast network of fjords, channels, and archipelagos extending from 42°S to Cape Horn (56°S). Some of these erosive marks, namely, the Magellan strait and the Beagle channel, have evolved into uninterrupted conduits that put in contact the Pacific and Atlantic oceans and thus must be considered together with the inflow across Cape Horn in the total transport of water and – mainly – properties into the Atlantic Patagonian shelf.

In its equatorward transit, the flow of waters of Pacific origin is supposed to also entrain part of the Beagle channel outflow before entering the SPS. Further north, the plume of relatively freshened waters is further diluted upon encountering the mouth of the Magellan strait at 52°S. Even though the flow through the Le Maire strait and the shelf-break dominates the volume transport into the SPS (Guihou et al. 2020), the outflow of the Magellan strait at 52°S is considered as the most significant contributor to the freshening of the SPS waters (e.g., Palma and Matano 2012).

The circulation in the SPS is complex due to its abrupt bathymetry, but the net transport is directed to the north and northeast, as a tongue of freshened waters mixed by winds and tides (Palma et al. 2008; Palma and Matano 2012). This body of freshened water, called the Magellan plume, progresses northward along the SPS controlled by the combined effects of the wind, tides, and western boundary currents (Palma et al. 2004; Palma and Matano 2012). Around the Magellan strait, the combination of strong tidal mixing and low-salinity coastal plumes generates frontal systems which show a semi-annual cycle changing their orientation from summer to winter (Rivas and Pisoni 2010).

The dominant winds interact with the morphology of the Grande bight at 52°S, resulting in a counterclockwise gyre at its southern part (Glorioso and Flather 1995; Palma et al. 2008). Cool and freshened northward flowing waters that originate in the Cape Horn current and the Magellan strait encounter that anticyclonic gyre of warm waters, forming a conspicuous front that extends northeastward from Grande bight. Flow divergence results in upwelling motions that may sustain the high primary and secondary biological production observed in the Grande bight and its surroundings (Schloss et al. 2007; Sabatini et al. 2016).

The Magellan Strait

The strait stretches for almost 600 km along a tortuous path, starting in the Pacific coast and opening to the Patagonian shelf at 52.5°S. The width and depth of the strait vary dramatically along its course, with depths >1,000 m at the Pacific entrance and only 70 m at the Atlantic mouth. Tidal amplitudes are also contrasting, from 1.2 m in the west to more than 7 m at its eastern limit (Panella et al. 1991; Fierro 2008). The net flow is, like in the rest of the region, eastward (e.g., Panella et al. 1991), implying a transfer to the Patagonian shelf of the freshened waters that infill the Magellan strait. Subantarctic waters enter the strait from the west and are progressively modified by continental inputs. At the Atlantic exit, modified subantarctic waters (Sievers and Silva 2008) with salinities 31–32 are injected into the SPS. Recently, Brun et al. (2020) estimated a net transport from the Pacific to the Atlantic along the Magellan strait of the order of 50,000 $m^3 s^{-1}$.

The Beagle Channel

Together with the interoceanic gateway that the Magellan strait represents, another uninterrupted though tortuous passage at latitude 55°S connects the Pacific ocean with the eastern coasts of South America: the Beagle channel. This 300-km-long conduit displays a very variable bathymetry, comprising small basins and bays with depths up to 400 m intervened by narrow and shallow sills 10–20 m deep. These features, combined with important freshwater inputs, have led some authors to suggest that the channel displays a fjord-like circulation (Isla et al. 1999). The mean surface flow is eastward, that is, from the Pacific to the Atlantic ocean (Balestrini et al. 1998), while more complex flow patterns are observed inside bays (Flores-Melo et al. 2020). In areas deeper than 50 m, the Beagle channel displays a seasonal cycle of vertical stratification, mainly controlled by freshwater inputs during spring and summer. In winter, reduced runoff and air-sea heat losses trigger the complete mixing of the water column by convection (Flores-Melo et al. 2020). The combination of seasonal stratification, sluggish flow, relatively high residence times (Cucco et al. 2019), and relevant inputs of organic matter from both natural and anthropogenic sources (Gil et al. 2011) result in the depletion of oxygen concentrations near the bottom at some sectors of the channel. This condition is particularly notable near the city of Ushuaia (Martin et al. 2016; Flores-Melo et al. 2020).

Tides in the channel are meso-microtidal with a range of amplitudes 0.67–2.18 m (D'Onofrio et al. 2016), contrasting with amplitudes up to 10 m in the northern sector of the SPS.

Observed Changes and Possible Consequences

Projections by IPCC (2014) signal high-latitude environments as those to be more likely affected by large climatic changes in the near future. The transport at the southernmost tip of South America is governed by a net transfer of water from the coastal Pacific to the Atlantic Patagonian shelf. Such transport is mediated by the prevailing westerlies and buoyancy forces. South of 50°S, winds impinging on the Pacific coast and associated precipitations have been increasing during the last decades according to Garreaud et al. (2013). Such changes can be associated with the observed positive trend of the SAM, which in turn has been associated with anthropogenic forcing (Marshall et al. 2006). The positive SAM trend reported by Marshall et al. (2006) would also lead to significant changes in the water mass characteristics (lower salinity) of the SPS (Guihou et al. 2020).

In fact, glacier retreat is being observed in the large ice fields of southern Patagonia (Bown et al. 2019) and is well documented in the eastern limit of the glacier distribution (Strelin and Iturraspe 2007).

An increase in freshwater inputs would result in an intensification of the Cape Horn current, implying larger water transports and increased dilution in the Patagonian shelf. In particular, in environments like the Beagle channel where tides are not strong enough to mix the water column, the strength of vertical stratification should increase in response to an eventual rise of runoff and water temperature, leading to a potential increase of frequency and intensity of hypoxic events.

Final Remarks

In this chapter we reviewed the main forcings that drive the ocean circulation in the Patagonian shelf with focus in the coastal regions. We also computed trends of satellite variables: SST, SSH, and Chl *a*. A significant positive trend (up to 0.04 °C per year) north of ~50°S and negative values (up to −0.02 °C per year) south of 50°S are observed. The negative SST trend observed in the southern portion of the region is associated with the positive trend observed in the dominant westerly winds within those latitudes. The spring Chl *a* linear trend observed shows values as large as 2 mg m^{-3} over a 10-year period in the outer portion of the continental shelf between 50 and 40°S. The linear trend in SSH ranges between 2 and 5 mm yr^{-1} (95% confidence level) in good agreement with previous results. In the northern region, the positive linear trends are associated with local changes in the density field caused by advective effects in response to a southward displacement of the South Atlantic High. Recent studies show that the SAM is one of the main players that might explain a portion of the interannual variability observed in the Patagonian shelf. Findings reported here are in agreement with the main results and predictions reported in the IPCC report for the southwestern Atlantic (IPCC 2014). A decrease in dissolved oxygen concentration and in pH (increasing ocean acidification) are also predicted (Bindoff et al. 2013).

In the northern Patagonian gulfs, the southward migration of the semipermanent South Atlantic High pressure system will induce a higher frequency of northerly winds. This scenario could favor the occurrence of coastal upwelling events and a decrease in the mixed-layer depth of up to 5 m per decade, as estimated by a global numerical model in the SMG and NG between 2003 and 2017 (Franco et al. 2018).

In SJG, more favorable upwelling conditions can be generated on the southern coast of the gulf as the result of an increase in the intensity of the westerlies that is expected as part of the climate change for these latitudes (Thompson et al. 2011).

In the southern Patagonia shelf, the increase of winds in the Pacific coast and associated precipitation can be associated with the observed positive trend of the SAM and affect the net transfer of water from the coastal Pacific to the Atlantic Patagonian shelf and therefore significant changes in the water mass characteristics (lower salinity) of the southern Patagonia shelf.

Accurate long time series of multiple physicochemical parameters is the limiting factor to produce the necessary knowledge to be able to adapt to and mitigate the climate change that the region is facing. Such measurements are difficult and expensive to obtain. Yet, they can make the difference to have the chance to preserve the Patagonian Sea as a healthy and productive ecosystem.

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Geological Changes in Coastal Areas of Patagonia, Argentina, and Chile

Federico Ignacio Isla and Manuel Fermín Isla

Introduction

The coast of Patagonia is usually considered as erosive because of the abundance of tall cliffs. The development of cliffs and the corresponding shore platform are ubiquitous in the Patagonian shores as well as global shores (estimated as representing 80% of worldwide shores). However, at the foot of most of those Patagonian cliffs, there are gravel beaches or extended gravel beach plains that were usually overlooked. These coastal deposits are part of the Quaternary evolution of the Patagonia, governed by complicated relationships between glacial processes, interglacial highstands, and uplifting trends. Patagonia is characterized by extensive accumulations of gravels derived from piedmont and end moraines to the west (proximal basinal environments) and by gravity-dominated phenomena (Patagonian Shingle) to the east.

Geologists discriminated wave-built barriers and wave-cut terraces in response to the sediment availability during the Quaternary highstands. However, the record of these coastal successions should be interpreted by considering both sea-level changes and uplifting rates. The widths of these Holocene plains differ from Atlantic to Pacific shorelines. At the fluvial discharges, estuaries and deltas have changed in relation to the climatic variations but also to the competition between Atlantic and Pacific watersheds. Some rivers, such as the Negro and Baker, increased their discharges, while others, like the Colorado, Chubut, and Deseado, reduced their flow.

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These changes in fluvial discharges conditioned not only the system own dynamics and the resultant deposits but other aspects important for human activities like the distribution of fish diversity.

The present contribution is a review of papers and theses not published about coastal areas of the Patagonia of Argentina and Chile. Reviewing processes has allowed to distinguish scenarios of both Atlantic and Pacific coasts and hence to understand the differences in the Quaternary evolution. Some coastal features should be envisaged in relation to projected changes (hydroelectric power plants) of some determinant variables. Several aspects describing the evolution of coastal systems such as their sedimentology, stratigraphy, geomorphology, and oceanography were also considered. In the descriptions, the Chilean areas are less accessible and covered by trees, compared to the Atlantic semidesert coasts.

Setting

The Patagonia region comprises four tectonic plates: most of the region occupies the southern portion of the South American plate; this portion moves relatively faster to the west, colliding against the Nazca and Antarctic plates. Nazca is an oceanic plate subducting below the South American plate north of 46°S (Folguera and Ramos 2002). South of that latitude, the Antarctic plate is also colliding. The Chile ridge signifies the growing of the Nazca and Antarctic plates, although it is also subducting below the South American plate causing volcanic and tectonic effects. The fourth component, the Scotia plate, comprises several microplates and the southern portion of the Fuegian archipelago (Bujalesky et al. 2021). Its relationship with the South American plate is along the Magellan transform fault system.

Most of Patagonia is characterized by a series of plateaus diminishing their altitude toward the Atlantic ocean (Feruglio 1950). Western Patagonia is conditioned by the structure and altitude of the Andes cordillera; however, the northern portion of this coast has another cordillera of less altitude called the Cordillera de la Costa. The Andes was drastically affected by the Quaternary glaciations (Caldenius 1932); the Patagonian ice field split into Northern and Southern ice fields about 11,000 years ago (Mc Culloch et al. 2000).

The coastal cliffs of eastern Patagonia extend from 40° to 53°S latitude. At the Fuegian archipelago, they extend to 56°S latitude (Fig. 1). The northern coast of Patagonia is conditioned by the extensive cover of shingle deposits during the Lower Pliocene. These covers are characterized by rounded gravels linked to a glaciofluvial origin. Originally named Patagonian Shingle formation (Darwin 1848), today they are known as the Tehuelche Gravels (Martínez and Coronato 2008) and are overlying the majority of the plateaus.

The Patagonia region also exhibits important climatic variations associated to the latitude. Mean temperature diminishes from 10 °C in northern Patagonia to 1–2 °C to the South (Coronato et al. 2008). Precipitation has different variations along both coasts: it diminishes from north to south at the Atlantic (Argentine) coast (from 51

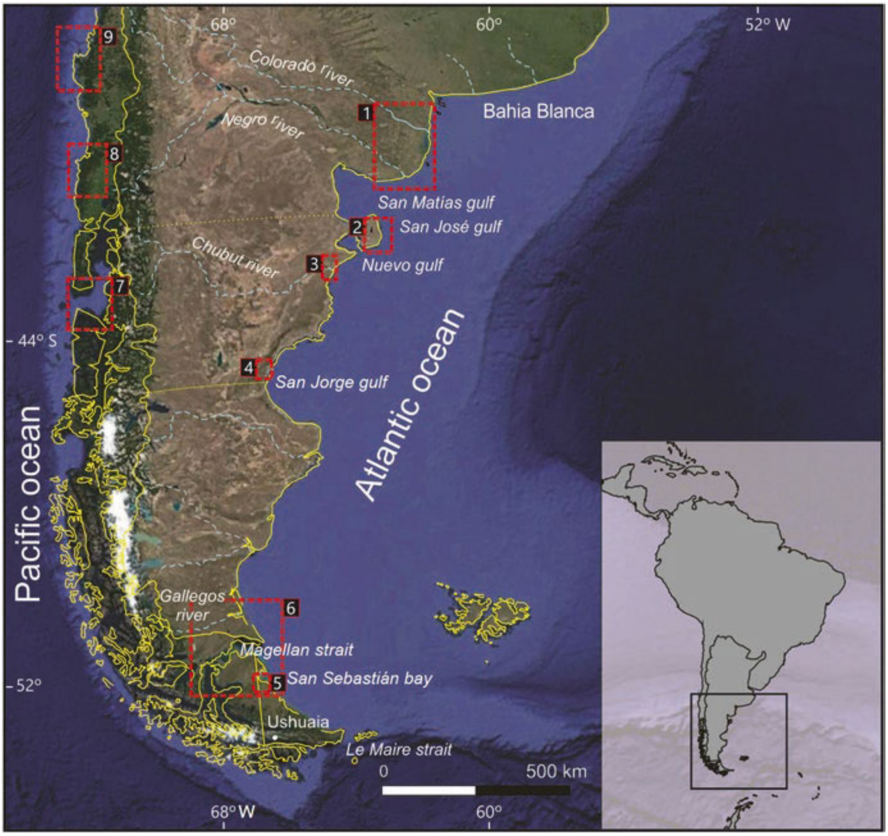

Fig. 1 Location of the areas described and analyzed in detail: (1) Colorado river delta and Negro river estuary; (2) Valdés Caleta; (3) Chubut river estuary; (4) Solano bay, San Jorge gulf; (5) Eastern Magellan strait; (6) San Sebastián bay; (7) Guaitecas and Chonos archipelagos; (8) Valdivia coast; and (9) Arauco gulf

to a minimum of 17 mm month^{-1}), increasing significantly at the eastern Beagle channel (44 mm/month in Ushuaia; Isla et al. 2010). On the Pacific (Chilean) coast, precipitation increases exponentially to 50°S latitude, decreasing further South (Araya Ojeda and Isla 2016).

The Atlantic coast of Patagonia is dominantly mesotidal, increasing to macrotidal (tidal range higher than 4 m, see Saraceno et al., this volume) toward the South and within some gulfs (San Matías, San José, Nuevo) and bays (Grande, San Sebastián) and the Magellan strait (Fig. 1). South of the Le Maire strait, the regime is microtidal as all along the Chilean coast. There is not much information about waves along the Patagonian coast; a useful approach is the report about the morphodynamics of some ocean beaches (Isla and Bujalesky 1995).

Regarding the altitudes of the highstands, their interpretations are quite different at the trailing-edge coast (Argentina) and at the active coast (Chilean). Uniform uplifts are assumed at both coasts for the Quaternary period (Pedoja et al. 2011; Isla and Angulo 2016; Jara-Muñoz and Melnick 2015). A regional uplift of 8–9 cm ka^{-1} has been estimated for the trailing-edge of the eastern Patagonia (Guilderson et al. 2000). On the western coast, the uplift of the Arauco peninsula was estimated between 120 and 180 cm/ka (Jara-Muñoz and Melnick 2015). At the Beagle channel (Fig. 1), the uplift was estimated in about 130 cm kyr^{-1} (Gordillo et al. 1992; Bujalesky et al. 2013).

For the middle Holocene highstand, the uplifting rates vary significantly for the Chilean and Tierra del Fuego coasts. In this sense, the altitudes of the deposits should be interpreted in relation to recent local effects, either uplifting or subsiding (Villalobos Silva 2005; Garrett et al. 2020; Quezada et al. 2020). Notwithstanding these behaviors between the eastern and western coast, sea level curves were proposed for the Magellan strait region (Porter et al. 1984; Bujalesky et al. 2013; Björck et al. 2021), the Atlantic southern coast (Schellmann and Radtke 2003), the northern coast (Isla 2013; Fig. 2), and the Chilean coast (Isla et al. 2012).

Quaternary Highstands and Terraces

The climatic variations that took place during the last 600,000 years were characterized by glaciations and marine highstands corresponding to interglacial periods (Fig. 2). Both extreme phases are evident in southern Patagonia and Tierra del Fuego. Glaciations left different deposits at both sides of the Andes. Although extended glaciations covered the Isla Grande de Tierra del Fuego and southern Patagonia, the last glaciation was limited to mountain valleys. At the Pacific coast, glaciers finished at the sea as fiords. Toward the Atlantic ocean, glaciers ended as piedmont glaciers, today mostly occupied by piedmont lakes.

Regarding the different tectonic conditions, uplifted marine terraces characterize the Chilean coast (Fig. 3A), while gravel and sand wave-built barriers are emplaced at the Argentinian coast (Fig. 3B). The topographic relationships between these highstands depend on the tectonic behavior and the sediment availability (Fig. 3C). The highstand of the Upper Pleistocene (also referred to as the Oxygen isotopic stage 5e, OIS5e) and those assigned to the highstand of the Middle Holocene are extended at the eastern Patagonian coast. On the Chilean coast, the last strongest earthquakes (1960 and 2010) caused very modern uplifted terraces that slowly become lower during the interseismic intervals (Quezada et al. 2020). Significant differences in the uplifting trends across the Magellan fault were estimated for the South American and Scotia plates (Bujalesky et al. 2021).

The eastern Valdés peninsula is located in the Atlantic coast of Argentina, specifically within the Chubut province (42°S latitude and 63°W longitude) (Fig. 1). The peninsula constitutes an important reserve of permanent and migrating marine and continental fauna (see chapters by Crespo and Quintana et al., this volume). Within this area, several gravel-dominated barriers are attached at different altitudes. Amino acid racemization techniques were applied to different mollusk shells,

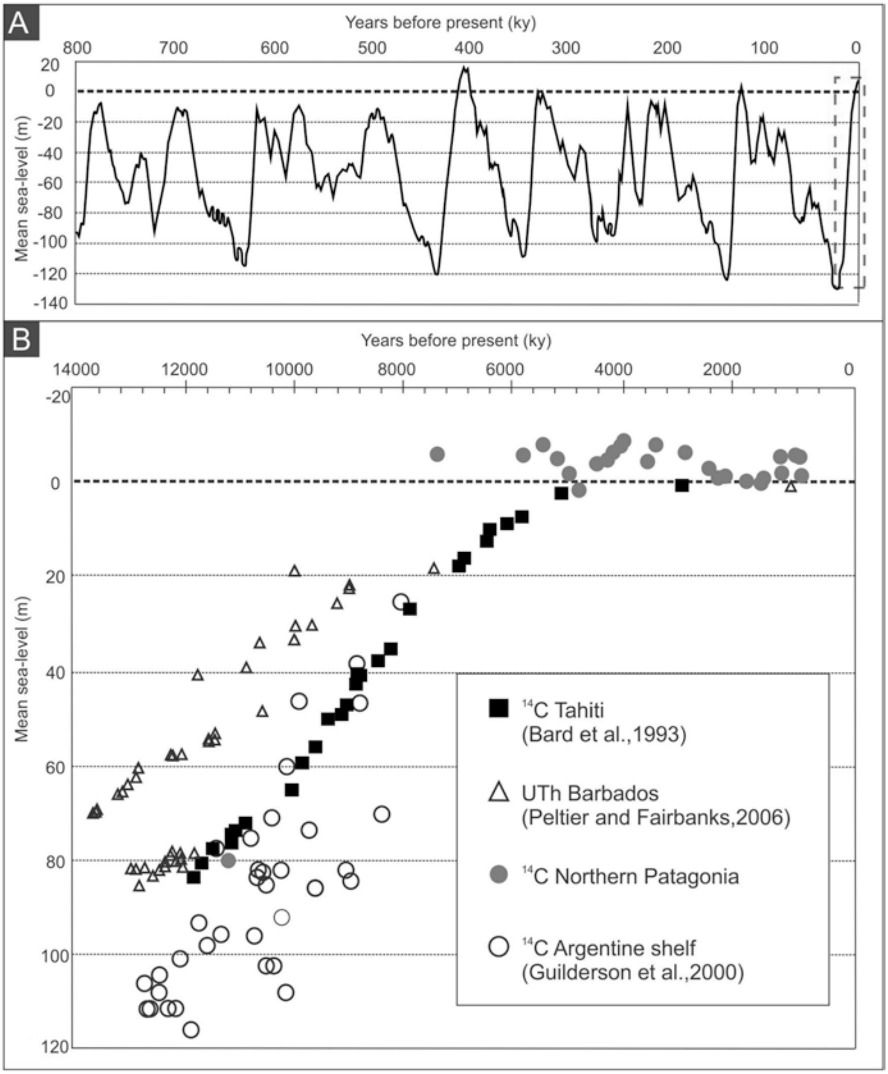

Fig. 2 (**A**) Pleistocene sea-level curve (modified after Spratt and Lisieki 2016). (**B**) Northern Patagonia sea-level curve. (Modified from Isla 2013)

most of them in living position. The oldest highstand is assumed to comprise the three highest barriers (I, II, and III; Fig. 3B) located between 26 and 35 m above mean sea level (Rutter et al. 1989). The ages of these systems were assigned to OIS7. System IV is about the same altitude, but the amino acid method indicated younger ages (possible OIS5e, 120 ka BP). The confusion about ages and altitudes of OIS7 and 5e was explained by a lower maximum height of OIS7 in relation to the higher OIS5e highstand (Rostami et al. 2000). System V is accepted as of Middle

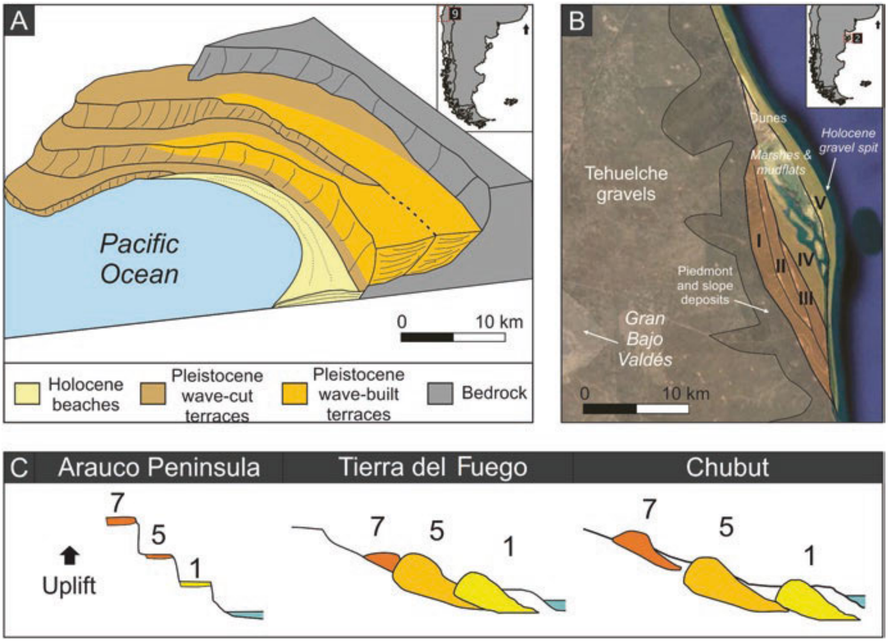

Fig. 3 (**A**) Arauco marine terraces, Chile (modified after Jara-Muñoz and Melnick 2015). (**B**) Sketch map of the Pleistocene marine highstands at eastern Valdés peninsula, Chubut, Argentina (modified from Rutter et al. 1989). (**C**) Topographic relationships in regard to the tectonic behavior and sediment availability. (Modified from Isla and Bujalesky 2008)

Holocene age and corroborated by radiocarbon dates (Rutter et al. 1989). The Valdés barrier encloses the Valdés caleta coastal lagoon and composed exclusively of gravel derived from the original Tehuelche Gravel formation; sand can be found beneath the gravel. This spit grew at a rate of 25 m yr.$^{-1}$ (Codignotto and Kokot 1988) increasing to 167 m yr.$^{-1}$ to the end of the twentieth century. Although a closure was forecasted, it never happened (Kokot et al. 2005).

The Upper Pleistocene highstand (OIS5) is extended into the Colorado river floodplain (Weiler 2000). Beach ridges are therefore remnants of an ancient open bay (Fig. 4).

Highstands of Quaternary age were repeatedly mapped at eastern Patagonia, and the ones corresponding to the OIS5e are preserved as tectonic-uplifted barriers from the original 6–8 m altitudes over MSL to levels of 18–25 m. The highstand corresponding to the OIS7 was lower than the OIS5e, and therefore it could only by discriminated where the uplifting trend was more significant. Notwithstanding these issues, highstands were reported at San Blas bay (Witte 1916), Bustamante bay (Schellmann 1998; Schellmann and Radke 2000, 2003, 2010), the Deseado river outlet (Iantanos et al. 2002; Zancheta et al. 2014), the Gallegos river outlet (Ercolano 2010), and northern Tierra del Fuego (Codignotto and Malumián 1981).

The Holocene Highstand and Regression

Several radiocarbon dates confirm the Holocene highstand and its regression at the Colorado river delta (Fig. 1), interfingered with gravel beaches between 6,630 and 1,300 years BP (Weiler 1993, 2000). The delta was built along a coastal plain limited by barrier islands (Spalletti and Isla 2003). When the Colorado outlet changed toward the north (New Lobe), these islands were eroded. During the regression, much of the sand delivered by the river was transported northward to construct the Patagones barrier islands (Fig. 4). Transverse and brachanoid dunes dominate to the NE, deriving sediment transported by the Negro and Colorado rivers (Cortizo and Isla 2012).

The Negro river originates by the confluence of two rivers (Limay and Neuquén) and entirely crosses its homonymous province before reaching the Atlantic ocean (Fig. 1). It was flooded by the sea during the Middle Holocene (Fig. 5). The Late

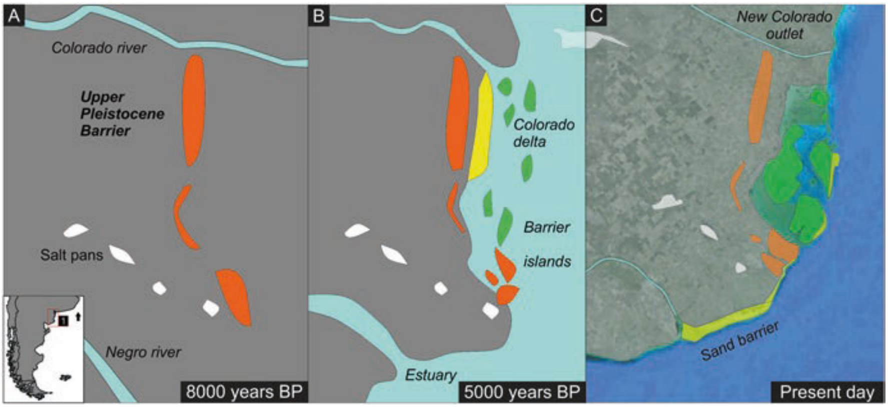

Fig. 4 Sketched Holocene evolution of the lower valleys of the Colorado and Negro rivers. (Modified from Weiler 2000; Cortizo and Isla 2012; Fayó et al. 2018)

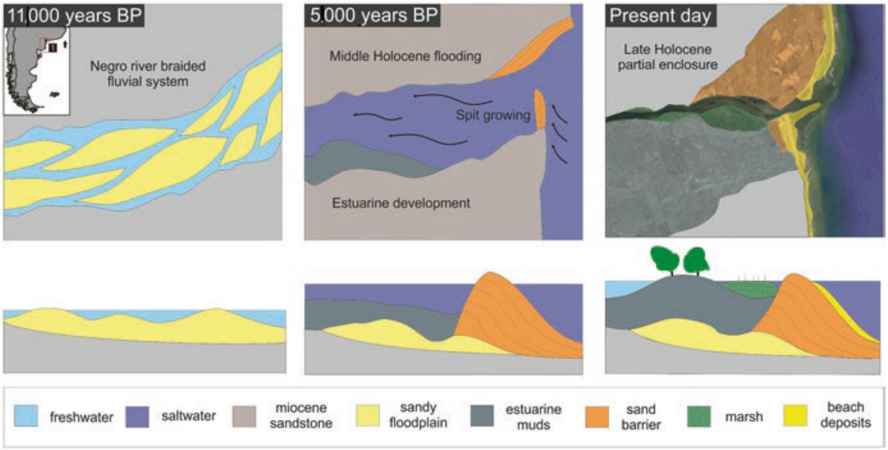

Fig. 5 Evolution of the Negro river inlet. (Modified after Escandell et al. 2009)

Holocene sea-level fall induced the deposition of estuarine muds at the floodplains and colonized by marshy vegetation (Escandell et al. 2009).

In the Chubut province, drift-aligned barriers evolved into swash-aligned barriers as soon as former depressions became completely enclosed. The Playa Unión barrier, located eastward from the city of Rawson, grew from north to south in relation to the migration of the Chubut river (Fig. 1). The growing of these complex spits occurred between 5,000 and 1,000 radiocarbon years BP (Monti 2000). More than 1.5 m of coastal marine facies is underlying marshes at Magagna beach (Fig. 6; Isla et al. 2015a, b).

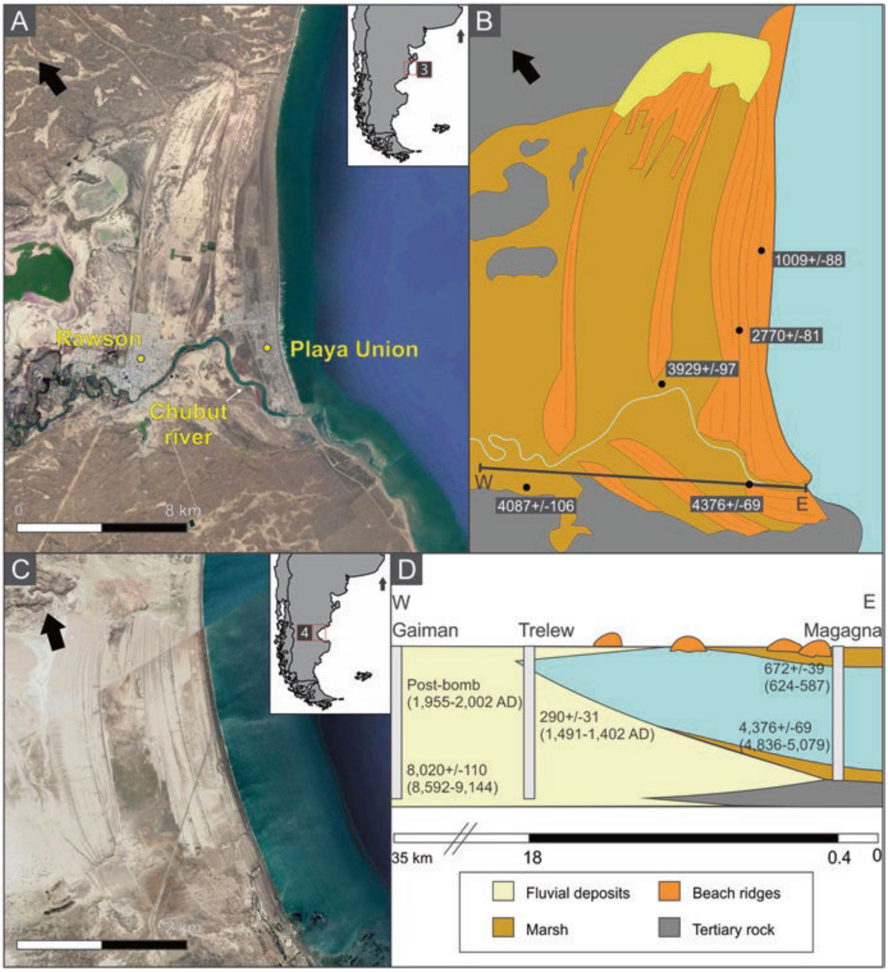

Fig. 6 Gravel beach plains prograded with a longshore drift from north to south. (**A**–**B**) Image and sketch map of the coastal plain of the Chubut river (Modified after Monti 2000). (**C**) Coastal plain of Solano bay. (**D**) Evolution sketch of the Chubut river plain. (Modified after Isla et al. 2015a, b)

In a similar way, a succession of beach ridges and spits growing from north to south enclosed Solano bay (Codignotto et al. 1987). This embayment is located in the SE boundary of the Chubut province, specifically 25 km to the north of the city of Comodoro Rivadavia (Fig. 1). Three systems were recognized: the first one spanning between 6,500 and 5,200 years BP, the second between 5,200 and 3,800 years BP, and the last one between 2,700 and 1,700 years BP (Fig. 6). Two coastal lagoons developed between the three barrier systems mostly composed of sand- and gravel-rich deposits (Codignotto et al. 1987). The case of Ensenada Ferrer, located in the NE extreme of the Santa Cruz province, is completely different: a former bay was modified into a coastal lagoon when the sea-level drop and induced by the growing of a spit anchored to former volcanic rocks (Medina et al. 2014).

In Santa Cruz province, the Deseado river inlet is located around 500 km to the NE from the city of Río Gallegos. Upper Pleistocene and Holocene highstands were mapped attached to the northern coast of this supratidal estuary (Zanchetta et al. 2014; Bini et al. 2017).

As it occurred along most of the South American coast, barriers and spits evolved in relation to the Mid-Holocene sea-level fluctuation (Isla 1989, Isla and Angulo 2016). Upper Pleistocene highstands were surveyed at the outlet of the Gallegos river (Ercolano 2010) and to the south of San Sebastián bay (Codignotto and Malumián 1981). Cuspate forelands grew to the south of the Buen Tiempo cape (Fig. 7; González-Bonorino et al. 1999) and Vírgenes cape (Dungeness spit, Uribe and Zamora 1981).

At the Magellan strait, between Otway sinus and Porvenir (52°50′ and 53°20’S latitude), Quaternary marine terraces were also mapped. The uppermost was levelled at 18–25 m of the Early Holocene age, although an Upper Pleistocene age was not discarded (Brambati et al. 1998). The Mid-Holocene highstand was recognized in several locations at 6–11 m over the mean sea level (MSL, 6,190 to 7,174 years

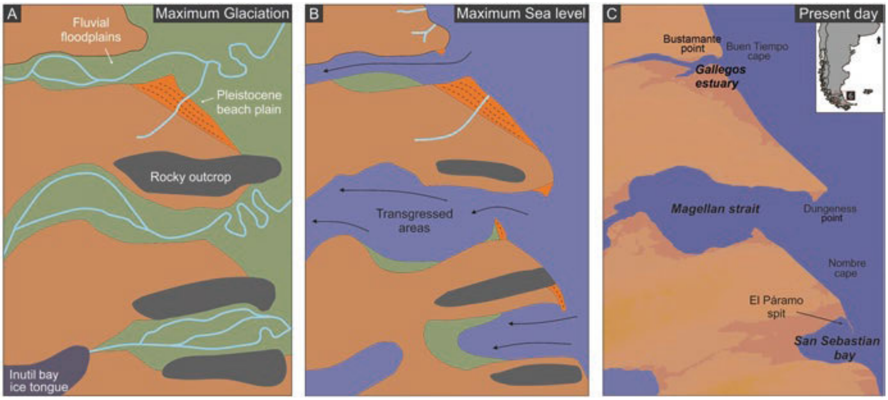

Fig. 7 Evolution of the Magellan barriers (Bustamante, Dungeness, and El Páramo spits). (**A**) Maximum glaciation, (**B**) Mid-Holocene maximum highstand, (**C**) present digital elevation model. (Modified from Bujalesky 1998; González-Bonorino et al. 1999; Ercolano 2010; Isla 2017)

BP), and at a lower stage of 3–5 m that was assigned to 2,500–1,200 years BP (Brambati et al. 1998). Uplifted Holocene terraces were also described at the northern entrance of Porvenir bay (De Muro et al. 2017) and at Juan Mazia peninsula (De Muro et al. 2015).

From Nombre cape, a similar cuspate foreland grew (Fig. 7); the gravel availability supplied from submerged moraines permitted the growth of the long El Páramo spit (Bujalesky 1998; Isla and Bujalesky 2000), enclosing the macrotidal flats of San Sebastián bay (Fig. 8; Isla et al. 1991; Vilas et al. 1999).

The Chico river complex spit was originally a simple flying split, very similar in its evolution to El Páramo spit but under higher sedimentation rates supplied by the river and within a shallower basin (Montes et al. 2018). A detailed sedimentological study applying different techniques permits to discern several stages including drift reversals (Bujalesky 2012; Montes et al. 2018). Other barriers from the eastern coast of Isla Grande of Tierra del Fuego are enclosing coastal lagoons (Falsa caleta; Isla and Bujalesky 1995) or partially blocked estuaries (Bueno river; Montes 2015).

Along the Arauco gulf, located southward to the city of Concepción, Chile (Fig. 9), several sites indicate Holocene sea-level sequences. Between San Pedro de la Paz and Coronel a beach ridge plain extends up to 6.3 km from the coast. Mollusk shell remains gave a radiocarbon age of 4,370 ± 90 years BP; further south, along the Carampangue coastal plain, broken shells gave older ages of 8,010 ± 90 years

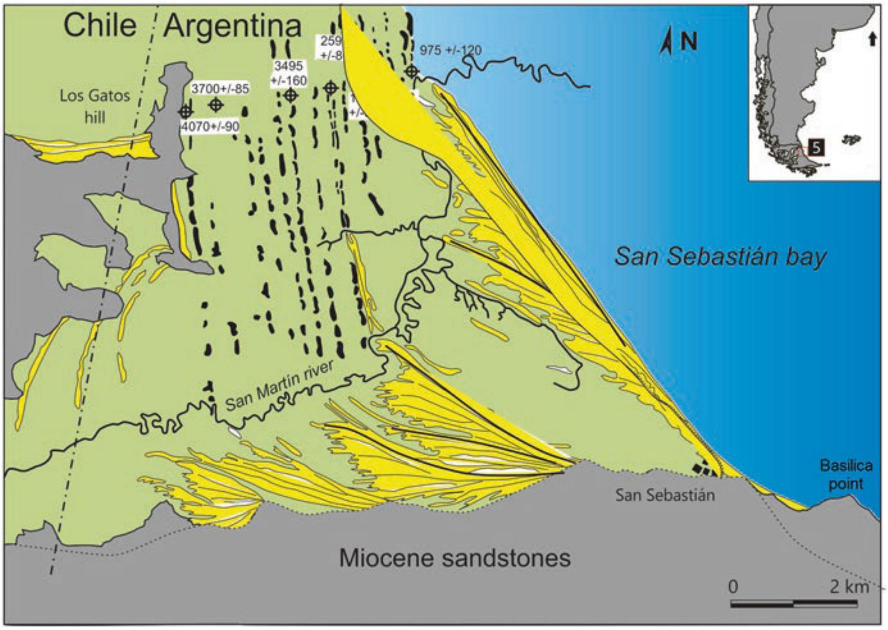

Fig. 8 Gravel beach plains indicate a regression from south to north. In the center of San Sebastián bay, the regression from west to east was recorded by carbonate remains from the chenier plain. (Modified after Isla et al. 1991; Vilas et al. 1999)

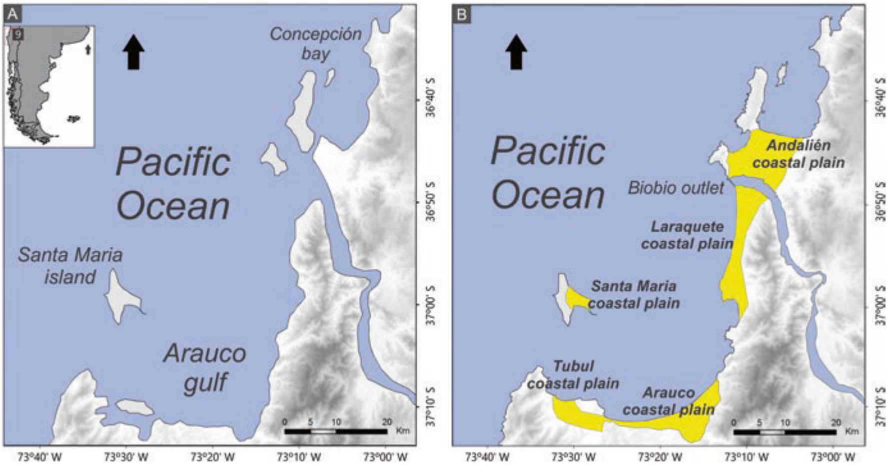

Fig. 9 Evolution of the Concepción bay and Arauco gulf (**A**) during maximum highstand 6000 years BP. (**B**) Holocene coastal plains. (Modified after Isla et al. 2012, 2019)

BP (Isla et al. 2012). To the west, at the estuary of the Tubul river, radiocarbon dates performed on shells remains of *Petricola rugosa* at 2.72 m over MSL also indicate Holocene ages of 4,780 ± 40 years BP (Garrett et al. 2020).

At the coast of Chan-Chan, north of Valdivia (Fig. 1), a beach deposit was occupied by former inhabitants during the Holocene (see Gómez Otero and Svoboda, this volume). Charcoal dates from the deepest levels (155–165 cm from the top) of the excavation gave ages of 5,610 ± 100 and 5,460 ± 50 years BP (Pino and Navarro 2005). Mancera island is located at the estuary of several concurrent rivers (Calle-Calle, Cau-Cau, and Cruces), close to Valdivia city. Three sea level terraces were discriminated: the highest belongs to the last interglacial, the intermediate to the Holocene maximum, and the lowermost was assigned to an uplifted terrace of the 1575 earthquake. The Holocene terrace was dated on 6,427 ± 60 years BP (Villalobos Silva 2005).

The Chiloé-Reloncavi region, between the 41° and 43°S, is characterized by evidences indicating coastal deposition above mean sea level (Hervé and Ota 1993). However, as the area was covered by piedmont glaciers during the Pleistocene and scarps related to the 1960 earthquake, it is very difficult to estimate absolute uplifting trends. Radiocarbon dates of coastal facies spanned from 3,130 ± 80 to 420 ± 80 years BP (Hervé and Ota 1993).

Southward from the Chiloé island, Holocene beach ridges and shell middens were also described at the Chonos archipelago, Aysén province (Fig. 1). Such coastal modern deposits overlie the metamorphic basement. The maximum altitude terrace (GUA-010, Gran Guaitecas) is reported at 5 m over MSL with a maximum age of 5,370 ± 30 years BP (Reyes Baez et al. 2016), although there are also evidences of submergence explained by local tectonic effects (Reyes 2020).

Changes in the Watersheds

Significant changes occurred at the Patagonian estuaries derived from geomorphological variations triggered mostly by climate but also by man-made structures (Tagliaferro et al. 2013). The Colorado river (Fig. 1) diminished its discharge due to the deactivation of the Desaguadero-Curacó river systems mostly during historic times (Spalletti and Isla 2003). These variations, with the addition of the infilling of the Casa de Piedra dam (1996) and the human alterations at the lower valley channels, impact seriously in the delta shoreline.

On the other hand, the Negro river (Fig. 1) has increased its discharge when, caused by the eruption of the Sollipulli volcano 2,900 ± 60 years BP, the river captured the drainage of the Moquehue and Aluminé lakes (Isla et al. 2019).

The Chubut river (Fig. 1) diminished its discharge when the Puelo river began to drain much of the upper watershed to the Pacific ocean (Isla and Cortizo 2014; Isla et al. 2015a, b). This diminution caused much of the fluvial terraces reported along the middle and lower valley (Auer 1959; Kokot 2004). The Deseado river also diminished its discharge, causing the rocky canyons that characterize the estuary (Iantanos et al. 2002). The origin of this discharge decrease was explained by a reversion of the outflow of the Buenos Aires-General Carrera lake. The Baker river captured two piedmont glacial valleys (Isla et al. 2015a, b; Isla and Espinosa 2021). The significant change in the discharge impacted initiated the rapid formation of the Baker delta and the significant decrease of the discharges of the Deseado and Pinturas river valleys.

These reversions in the directions of the fluvial discharges (Atlantic to Pacific, and vice versa) should explain former variations in the fish communities (Isla et al. 2015a, b).

Cliff Retreat and Sea Level Trends

Cliff coastal erosion along eastern Patagonia was estimated comparing photographs (1964–1971) and images (2001–2003); it varies between 0.3 and 1.4 m yr.$^{-1}$, being more pronounced at capes (Isla and Cortizo 2014). For the interval 1986–2016, it was estimated that 24% of the world's sandy beaches are eroding at a rate of exceeding 0.5 m yr.$^{-1}$, while 28% are accumulating and 48% are stable (Luijendijk et al. 2018). Receding rates are assumed to increase worldwide in relation to the anthropogenic sea-level rise, forecasted between 0.43 and 0.84 m for year 2100 (Oppenheimer and Glauvovic 2019).

Applying models for application at regional scales (MARS), forecasted sea-level rise rates indicate changes of the M_2 component of the Patagonian tides, with reduction at southern Patagonia and northern Tierra del Fuego, and increments toward Valdés peninsula (Clara et al. 2015). Wave setup can also increase local sea-level rise (Melet et al. 2020), mostly in a windy hemisphere.

On the Chilean coast, most of these sea-level trends should be handled cautiously in relation to the behavior of the coast during major earthquakes (1960, 2010) and their intercoseismic intervals (Quezada et al. 2020). In relation to the scenarios proposed by the Intergovernmental Panel on Climate Change (IPCC), Northern Chile would have a higher sea-level rise than Southern Chile (Albrecht and Shaffer 2016).

Conclusions

Patagonian coast evolved in relation to the sea level fluctuations that characterize the Quaternary. Those changes controlled periods of progradation and retrogradation of coastal environments that in some cases resulted in complex stratigraphic records. However, the uplifting trend is different at the Atlantic and Pacific coasts. For example, the Fuegian coast has been subject to local tectonics, while the glacio-isostatic uplift should be presently considered as minimum.

The coast has been modelled by valleys eroded by rivers that used to discharge more water and glaciers that melted during the Upper Pleistocene. Marine terrace dimensions differ according to their tectonic rates, tidal ranges, and sediment availability.

In relation to the forecasted anthropogenic sea-level rise, the availability of gravels derived from the Andes would protect bays, marshes, and estuaries from the erosion effects. On the contrary, those areas where sand deposits become dominant would be more susceptible to coastal erosion.

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Past Sea Incursions into Patagonia and the Resulting Record of Marine Invertebrates

Miguel Griffin, M. Alejandra Pagani, and Susana Damborenea

Introduction

The current coast of Patagonia spans about 14° of latitude from the mouth of the Negro river down to Tierra del Fuego. Along this coast lives a diverse flora and fauna derived from complex changes in climatic conditions, paleogeography and paleoceanography that occurred in the area and beyond since the opening of the Atlantic ocean (Lawver and Gahagan 2003; Cuitiño et al. 2019). From that moment on, the shoreline has undergone great variations in outline and position in relation to the current coast, reflecting several transgressive/regressive events of the Atlantic ocean onto the continental mass of this region of South America at different moments during the Cretaceous and Cenozoic (Macellari 1988a; Malumián and Nañez 2011). The causes of such events are manifold, and a detailed discussion is beyond the scope of this chapter (see Navarrete et al. 2020). Yet, the geological and paleontological record they left behind has been preserved in many instances, a fact allowing us to grasp the changes in environment that took place there, together with the variations in fauna and flora that such changes triggered. Lying along the present

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coastline of Patagonia, extensive exposures of marine rocks reveal the geological history of the area during the Cenozoic, while Mesozoic rocks exposed further to the west, along the foothills of the Andes, bear witness to the early stages of the South Atlantic.

Although the presence of fossils in rocks along the coast has been known for well over three centuries, scientific interest in them arose only in the early nineteenth century, following the pioneering work by d'Orbigny (1834–1847) and Darwin (1846). Ever since then, a growing body of knowledge has led to a better understanding of the stratigraphy and paleontology of Patagonia (for detailed discussions and further references, see del Río 2004a, b; del Río and Camacho 1996, 1998; Griffin and Nielsen 2008). Along the way, great advances in different areas of geology provided increasingly accurate pictures on the evolution of the South Atlantic. These, in turn, helped to understand the origin and evolution of the marine faunas living in the region at different times and the relation of such faunas with the evolving paleoceanography and paleoclimate accompanying the opening of the Atlantic and the seaways connecting it with other oceanic masses right up to its present configuration (Beu et al. 1997, and references therein).

In this chapter we briefly summarize the major flooding events of the Atlantic ocean, their fossil record, and the general characteristic of the faunas associated to them and to the paleoclimatic and palaeoceanographic conditions.

Pre-Atlantic Context

The development of today's life in Patagonian coasts is related to the relatively recent geological history of the South Atlantic ocean. Nevertheless, other much older coastal marine ecosystems developed in what is now Patagonia. Their fascinating history amply predates the opening of the South Atlantic and can be traced back to Early Paleozoic times. Plunging into deep-time seas, we will summarize their pre-Cretaceous history in the frame of a changing Earth context.

Early Paleozoic

The oldest shallow water fossils found in Patagonia are Cambrian archeocyaths, a short-lived group of shallow water calcareous sponges (González et al. 2011). Although these are allocthonous fossils found in blocks most probably derived from Early Cambrian limestones from the Transantarctic Mountains (East Antarctica), this record revived the hypothesis that at least part of Patagonia was a terrane detached from Gondwana at that time (see discussion in Ramos and Naipauer 2014, and references therein). The same rocks contain also in situ linguloid brachiopods,

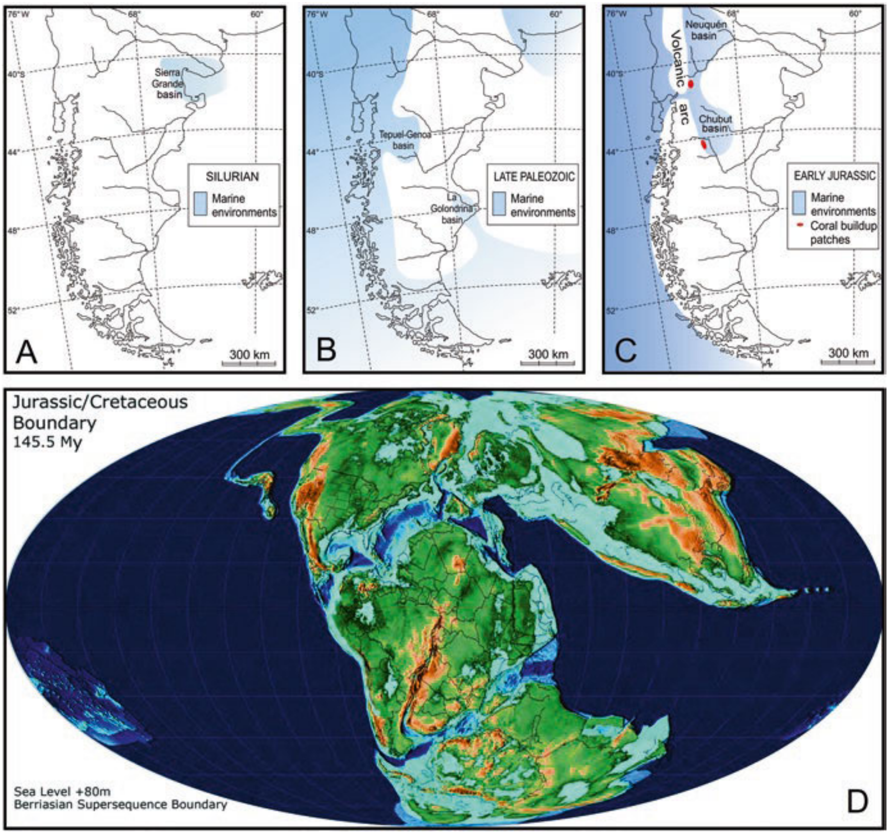

Fig. 1 Main marine environments in Patagonia before the opening of the South Atlantic. The map of Patagonia showing the location of marine sediments during: (**A**) Early Paleozoic (Silurian), (**B**) Late Paleozoic, and (**C**) Early Jurassic. (**D**) Global paleogeography at the Jurassic/Cretaceous boundary, before the opening of the South Atlantic ocean, slightly modified from Scotese (2014b), map 32. Mollweide Projection, CR Scotese, PALEOMAP Project

as mentioned by Braitsch (1965), who referred them to pre-Silurian Early Paleozoic. Yet, the oldest diverse marine fauna from Patagonia was described by Müller (1965) from northeastern Río Negro province (Sierra Grande region, Fig. 1A) and is dated as Early Silurian (Rustán et al. 2013). It includes several trilobites and brachiopods, conulariid cnidarians, and also bivalves, gastropods, nautiloids, hyoliths, corals, crinoids, and ichnofossils (Müller 1965; Manceñido and Damborenea 1984; Rustán et al. 2013). The Silurian shallow platform where this diverse but still poorly known fauna developed had firmgrounds (Manassero et al. 2014) and was probably part of a continental interior epeiric basin located between southern South America and southern Africa.

Late Paleozoic

Late Paleozoic marine rocks are preserved in Patagonia mostly along the western area of the Chubut province, in the Tepuel-Genoa basin. In the eastern area, rocks of this age are exposed only in the La Golondrina basin, representing the southernmost record of Late Paleozoic rocks. These rocks show an interesting succession of fossil-rich latest Carboniferous-Early Permian deposits (Archangelsky et al. 1996).

The widespread sea transgression in central-western Patagonia during the Carboniferous and Permian renders it a special place to study Late Paleozoic life and environmental change because of the excellent exposures of the sedimentary sequences. The Tepuel-Genoa basin (Chubut province) is located on the southwestern margin of Gondwana at this time (Fig. 1B). These outcrops spread over extensive areas between 43°–44°20′S and 69°30′–71°W and are distributed for approximately 250 km along a north-northwest to south-southeast direction. The marine Late Paleozoic of Patagonia carries abundant and well-preserved representatives of most invertebrate groups: brachiopods, bivalves, gastropods, cephalopods, hyolithids, pelmatozoans, ostracods, and cnidarians. This biota is associated with several glacial-related horizons and interglacial intervals and was developed under cold paleoclimatic conditions due to the high paleolatitudinal setting of Patagonia.

The composition of the Patagonia biota was affected by a global decrease in temperature during the Late Paleozoic ice age, which caused marked differences between the biotas of paleopolar regions and those in the paleoequatorial belt (Isbell et al. 2013). Patagonia contains a diverse record of palaeobiological events, which seems to indicate a very different evolutionary pattern and more paleoclimatic fluctuations relative to other adjoining Gondwana areas. The faunal assemblages show different paleogeographic links. During the middle Carboniferous, the Patagonian sea was characterized by a cold-water fauna with key elements present in western Argentina, Antarctic peninsula, and eastern Australia. Later, during Pennsylvanian-Early Asselian times, the faunal communities became highly endemic. Finally, the younger cool- to cold-water faunas in Sakmarian-Artinskian times reveal strong paleobiogeographic links to western Australia and the Cimmerian regions of south and southeast Asia. At this time, the migration pathway between the southwestern margin of Gondwana and eastern Australia also appears to have been re-established, as evidenced by the key faunistic elements shared among these areas (Pagani and Taboada 2011; Taboada and Shi 2011; Taboada et al. 2005, 2013, 2016).

These distinctive paleobiologic events in the Late Paleozoic of Patagonia display key evidence for constraining the paleogeographic setting of Patagonia and a better understanding of the paleobiogeographic, paleogeographic, and paleoclimatic evolution of this part of southern Gondwana. For a detailed discussion about these issues, see Pagani and Taboada (2010, 2011), Taboada (2010), Taboada and Pagani (2010), Taboada and Shi (2011), Taboada et al. (2019), and references therein.

Mesozoic

During the Early Jurassic, there was a relatively short but widely expanded sea transgression in north-central Patagonia, roughly in the same areas of the Late Paleozoic sea just described. Then and there, a shallow marine basin developed, which was separated from (but also connected with) the Pacific ocean by a volcanic arc and was most probably linked to the Neuquén basin to the north (Fig. 1C). Marine sediments appear intercalated in a mostly volcaniclastic sequence and bear a diverse invertebrate fauna with bivalves, ammonoids, gastropods, brachiopods, scleractinian corals, sponges, serpulids, crinoids, echinoids, and occasional crustaceans (some species first described by Feruglio (1934) and Carral Tolosa (1942); see updated references in Ferrari (2014), Damborenea and Pagani (2019)). Bivalves (about 80 species) and gastropods (about 40 species) are the better-known groups. The ammonoids indicate that this extensive sea lasted about 10 million years between the Late Pliensbachian and Early Toarcian (Musacchio and Riccardi 1971; Blasco et al. 1979).

The benthic associations contain both body fossils and ichnofossils, which are related to diverse paleoenvironments, characterized by different substrates and water energy conditions (Pagani et al. 2011, 2012; Ferrari 2014; Ferrari and Bessone 2015; Damborenea and Pagani 2016). All the associations are dominated by bivalves. Three main – and several more specialized – fully marine environments can be recognized: (A) in high-energy, well-oxygenated and shallow coastal environments, the fauna is most diverse, with large shells of bivalve and gastropod species of the genera *Weyla*, *Cardinia*, *Ctenostreon*, *Isocyprina*, *Groeberella*, the trigoniids *Promyophorella* and *Jaworskiella*, and the vetigastropods *Lithotrochus*, *Calliotropis*, and *Chartronella*, among others. Locally, scleractinian colonies may form isolated reef patches and support a variety of epizoan, nestling and boring invertebrates. (B) At the same time, in somewhat deeper and less energetic settings, shallow burrowers, such as astartids and trigoniids (*Frenguelliella* species) are common, together with species of *Pleurotomaria* and *Globularia* and several brachiopods; when local conditions include quiet waters and organic-rich bottoms, the benthic fauna is dominated by very active detritivorous, shallow-burrowing protobranch bivalves. On the other hand, the peculiar ichnogenus *Lapispira* appears in storm-dominated shoreface deposits of the basin (Pagani et al. 2012). (C) In still, quieter, platform environments, the poorly diverse associations are dominated by paper clams (*Posidonotis*) and other epifaunal bivalves (*Kolymonectes*, *Parvamussium*, *Agerchlamys*, *Parainoceramya*) and small *Procerithium* and *Ambercyclus* gastropod species. Locally, rapid burial in this last type of environment allowed the unique preservation of a nearly complete exoskeleton of one of the oldest known glypheoid decapod crustacean *Mecochirus* (Pagani et al. 2011).

Early Jurassic marine bivalves from north-central Patagonia are mostly the same as those from the Neuquén basin, but some differences and gradients attributed to paleolatitude have been noticed (Damborenea and Echevarría 2015). These include (A) as expected, bivalve generic diversity decreases toward the south; (B) in

Patagonia there are some endemic species belonging to high paleolatitude genera, such as *Ryderia*, *Ochotochlamys*, and *Notoastarte*; (C) some bivalve groups show relative diversity proportional increases toward the south (Crassatelloidea, Nuculanoidea, Pectinoidea, Monotoidea), which suggests that latitudinal trends of some living bivalve lineages may have a longer and more complex history than previously thought.

Early Stages of the Atlantic Opening: Latest Cretaceous

The latest Jurassic entailed the onset of a rift system that marked the beginning of the separation of Africa and South America in the general context of the fragmentation of Gondwana (Benedetto 2010). Together with this fragmentation, a series of basins developing along the rift record the changing environmental conditions, from continental to marginal marine and eventually fully marine (Fig. 1D). Extensional crustal spreading in the Late Jurassic originated most sedimentary basins in Patagonia. One of them, containing a large proportion of the fossil faunas living in the area during the Cretaceous-Cenozoic, is the Austral-Magallanes basin (Cuitiño et al. 2019, and references therein). The initial continental infilling of this basin gradually gave way to marginal marine deposits.

Atlantic Ocean Context

Cretaceous

By the Early Cretaceous, the first of the Atlantic transgressions deposited marine fossil-bearing sediments as far north as northwestern Santa Cruz (Hatcher 1900; Riccardi 1988) (Fig. 2). Several lithostratigraphic units reflect the variety of environments that this transgression spurred, many of them containing moderately abundant marine invertebrates with elements in common with faunas from other shelf areas of different fragments of Gondwana now drifting apart. Different faunas of this age range have been described over the years (von Ihering 1903, 1907; Feruglio 1936; Griffin and Hünicken 1994, among others). Some of the typical taxa of this period in the Austral basin are ammonoids (e.g., *Maorites densicostatus*, *Grossouvrites gemmatus*), bivalves (*Inoceramus*, *Aucellina*, *Austrotrigonia*, *Pacitrigonia*, *Australoneilo*), gastropods (*Austrosphaera*, *Austroaporrhais*), and other invertebrates such as bryozoans, decapods, balanids, and echinoderms. These faunas include, with varying diversity, some taxa (mainly mollusks) that originated in the southern latitudes and are known generically as Paleoaustral elements defining the high-latitude Weddellian province (Zinsmeister 1982).

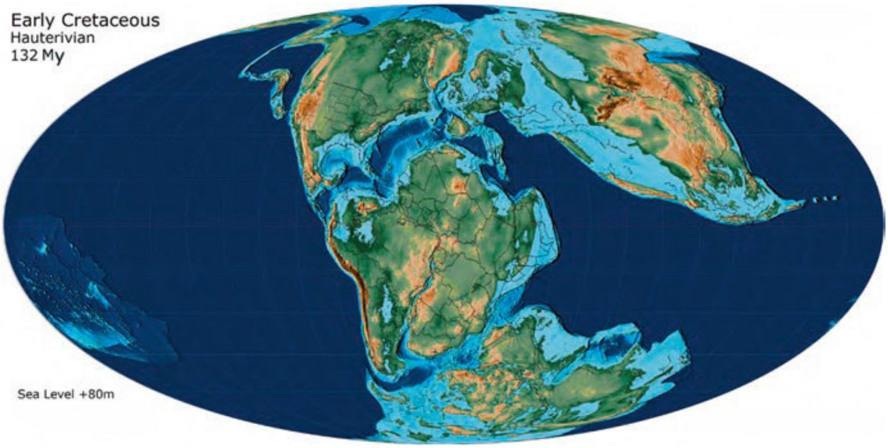

Fig. 2 Early stages of the South Atlantic. Global paleogeography during the Early Cretaceous, at the onset of the opening of the South Atlantic ocean, slightly modified from Scotese (2014a), map 29. Mollweide Projection, CR Scotese, PALEOMAP Project

Tectonic events at the end of the Cretaceous changed the extensional character of the basin to a compressional regime, with a progressive southbound continentalization evident in the marginal marine to frankly terrestrial environments that can be found north of Argentino lake. Marine conditions persisted further south, where the transition to the Paleogene is recorded in marine sequences, containing a rich fauna of mollusks and other invertebrates of Maastrichtian to Paleocene age. With the onset of deep-water conditions between the different fragments of Gondwana (South America, Antarctica, and Australia/New Zealand), together with the evolving paleogeography of the southern continents and their shelf areas, a gradual change in the characteristics of the fauna began, showing increasing influence of taxa originated beyond the Gondwana realm (del Río 1992, 1994, 2004a; Beu et al. 1997; Martínez and del Río 2002; del Río and Martínez 2015).

In northern Patagonia, the first transgressive event from the Atlantic ocean began later than in the Austral basin. This flooding advanced westward onto the continent, covering large areas of northern Patagonia and adjacent regions, reaching over parts of the provinces of Chubut and Río Negro westward up to western La Pampa, Neuquén, and southern Mendoza. This transgression, occurring during the Maastrichtian, was the last marine event in the Neuquén basin, covering the older Mesozoic deposits originated in the Neuquén embayment of the Pacific ocean. These rocks contain a rich fauna of invertebrates, including a diverse assemblage, mainly of mollusks (*Australoneilo*, *Austrotrigonia*, *Pacitrigonia*, *Lahillia*, *Roudaireia*, *Plicatula*, *Turkostrea*, *Camptonectes*), bryozoans, decapods, and echinoderms (Burckhardt 1901; Weaver 1928; Feldmann et al. 1995; Parma and Casadío 2005). Some taxa (e.g., *Austrotrigonia*, *Lahillia*, *Australoneilo*) show affinities with the Weddellian province, while others (e.g., *Roudaireia*, *Plicatula*, *Camptonectes*) are instead taxa of Tethyan origin, i.e., in the Tethys Sea, opening eastward between

Laurasia and Gondwana from approximately the area now occupied by the Mediterranean (Casadío et al. 2005; Aguirre-Urreta et al. 2008). Notably missing in the Neuquén basin is the family Kossmaticeratidae that is quite diversified in the Austral basin (Macellari 1986, 1988b).

Maastrichtian rocks in the Neuquén basin are topped by the Cretaceous/Paleogene boundary. In northern Patagonia, the shallow Maastrichtian sea persisted into the Paleocene before receding until the much later Miocene transgression, albeit never again to reach the extent it had during the Maastrichtian. Water temperature was above 25° according to Woelders et al. (2017).

Paleocene

Paleocene rocks in Patagonia are concentrated in three different areas (Fig. 3). In the southernmost part of the continent, within the Austral basin, there are Paleocene rocks exposed along the foothills of the Andes in Tierra del Fuego and southwestern

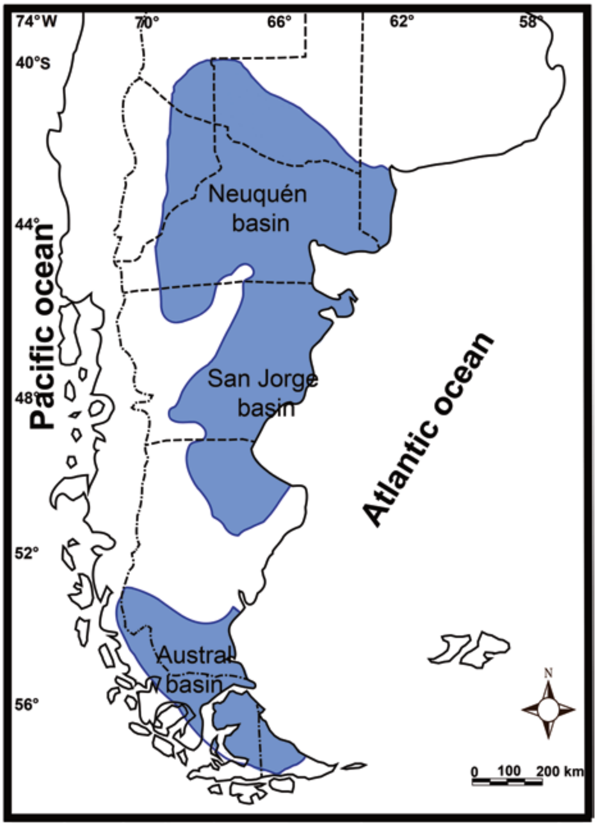

Fig. 3 Main marine environments in Patagonia during the Cenozoic history of the South Atlantic. Late Cretaceous/Paleocene

Santa Cruz provinces (Camacho 1992; Malumián and Nañez 2011). These rocks overlie Maastrichtian marine rocks, and, while geographically restricted, they are important because they contain a fauna that still shows a Paleoaustral character, with many taxa that reveal a common origin with taxa from other regions of the southern continents (Zinsmeister 1982; del Río 2012; del Río and Martínez 2015). They have been generally considered as Danian in age, although recent detrital dating suggests that at least the deposits outcropping in southwestern Santa Cruz province and assigned to the Cerro Dorotea formation may be Selandian (Fosdick et al. 2020).

Further north in Patagonia, the Paleocene sea-flooded areas of Santa Cruz and Chubut provinces in the San Jorge basin, where outcrops can be found, scattered over a large area, but mainly at the Chico and Chubut rivers junction, and along the coast between Visser port and Malaspina bay, where they lie almost at sea level. These rocks, known as "salamanquense," contain a diverse fauna of mollusks and other invertebrates, with some taxa shared with the fauna of the Austral basin (*Darwinices*, *Pseudamaura*) and others that appear to be unique to this period in the region (*Odontogryphaea*). This shallow-water fauna lived in warm temperate waters – albeit with fluctuations – as did the Maastrichtian-Paleocene faunas in the Austral basin. An example of this is the decapod crustacean *Costacopluma* (Feldmann et al. 1995).

In northern Patagonia, the great Maastrichtian flooding persisted into the Paleocene. After the general warming trend until a decrease in water temperature at the end of the Maastrichtian, a warming in shallow waters occurred during the Danian, evidenced by carbonatic and evaporitic rocks and even coral reefs – albeit restricted – in western La Pampa (Carrera and Casadio 2016). Outcrops of Paleocene rocks are common at several places in the Neuquén basin, especially in western Río Negro, eastern Neuquén, southwestern La Pampa, and along the western shore of the San Matías gulf. The faunas are generally poorly preserved, and the most conspicuous elements are those with calcitic shells or skeletons, such as oysters, pectinids, echinoderms, and bryozoans.

The faunas included in the Paleocene deposits were studied by Burckhardt (1901), Ihering (1903, 1907), Feruglio (1936), Petersen (1946), Camacho (1949), Griffin and Hünicken (1994), Casadio (1998), Griffin et al. (2005), del Río et al. (2007), and del Río (2012). For a detailed discussion on the Paleocene faunas and their biogeographic affinities, see del Río and Martínez (2015). Most of the fauna includes cosmopolitan taxa together with Paleoaustral temperate taxa such as *Perissodonta*, *Lahillia*, *Neilo*, *Darwinices*, *Austroaporrhais*, *Pseudofax*, *Globisinum*, *Microfulgur*, *Zemacies*, and *Priscaphander*. However, some taxa with northern hemisphere affinities such as *Acesta* (*Pliacesta*), *Gryphaeostrea* and *Phygraea*, *Heteroterma*, *Priscoficus*, and *Clairbornicardia* are also common.

Eocene

Eocene marine rocks are poorly represented in the geological record of Patagonia. The paleogeographic configuration during this time shows that there were three areas in which Eocene sediments were deposited. In the southern and southwestern reaches of the Austral basin, an embayment with a sea of variable depth stretched from the Southwest Atlantic in a northwestern direction until just north of Argentino lake (Fig. 4). The sediments deposited there can be recognized in Tierra del Fuego, in the Río Turbio area, and in the Argentino lake area, where they appear outcropping along the foothills of the Andes. The only fossil-bearing rocks of this age in the basin exposed along the current coastline lie in Tierra del Fuego, at San Pablo cape. They contain an impoverished and poorly known fauna that appears to reflect the

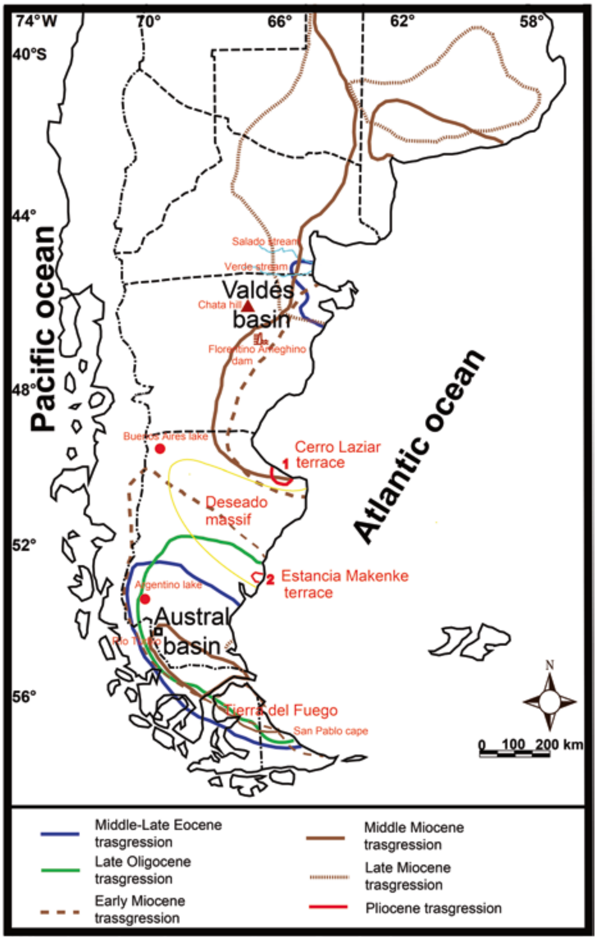

Fig. 4 Main marine environments in Patagonia during the Cenozoic history of the South Atlantic

warmer conditions brought about by the Middle Eocene Climate Optimum (Zachos et al. 2001; Bohaty and Zachos 2003). In the Río Turbio area, the faunas of this age are very poorly preserved, including bivalves, gastropods, echinoderms, and balanids. While taxonomic identifications are difficult, some characteristic Paleoaustral elements can still be recognized, such as *Paleoneilo*, *Cucullaea*, *Lahillia*, *Perissodonta*, and *Spirogalerus*. Endemic fauna is represented by *Neovenericor*, *Austrocallista*, *Ameghinomya*, and *Valdesia*, among others (Griffin 1990, 1991; Camacho et al. 2000a, b; Casadio et al. 2009).

Sedimentation occurred in a shallow warmwater sea and is reflected in a characteristic Mn-rich limestone with a small and poorly preserved fauna of bivalves (*Lima*), gastropods (*Polinices*, *Campanile*), nautiloids, and echinoderms and also carrying a fairly diverse flora of algae (Rossi de García 1959; Rossi de García and Levy 1977; Ravazzoli et al. 1982; Leguizamón et al. 1993). The outcrops of these rocks are scattered along the coast between Salado and Verde streams, and a few other localities in Chubut province, namely, along the bed of the Verde stream, at Chata hill and near the Florentino Ameghino dam further south. The age of these rocks has not been clearly established, but they have been deemed to be Middle to Late Eocene based on their fossil content.

Late Eocene-Oligocene

Sediments of Late Eocene to Oligocene age deposited in the Río Turbio area in the Austral basin (Fig. 4) – represented by the upper member of the Río Turbio formation – reflect changing paleoceanographic and paleoclimatic conditions resulting from the onset of cooler seawater circulation in areas surrounding Antarctica at the time as a result of deepening conditions along Bass strait and Drake passage. Detrital ages for this lithostratigraphic unit suggest ages ranging between 37 and 27 My (Fosdick et al. 2020). These rocks contain a fauna that already shows some influence of other biogeographic realms, in a pattern somewhat similar to that shown by dinocysts in the Río Turbio formation, with a progressive trend toward the replacement of Antarctic taxa by other with a more cosmopolitan character (González Estebenet et al. 2015, 2017). Among some of the taxa of mollusks new to Patagonia that appear in these beds are *Yoldia* (*Calorhadia*), *Lahillia*, *Periploma* (*Aelga*), *Neovenericor*, *Clavipholas*, *Modiomytilus*, *Purpurocardia*, *Electroma*, and *Sigapatella* (Griffin 1990, 1991).

Late Oligocene rocks appear to be exposed further east in the Austral basin, i.e., in the Gran Bajo de San Julián and along the coast in a small area near the town of Puerto San Julián. The relationship of these rocks with those exposed in the Río Turbio area have not been established yet, but they were probably deposited during the same transgressive cycle. In the Puerto San Julián area, these rocks are known as the San Julián formation and carry a diverse and abundant fauna of invertebrates. The faunal composition is biased toward calcitic organisms, as most aragonitic shells are leached and only molds or calcite replacements have been found. Among the well-preserved calcitic-shelled taxa, the most common are oysters (*Crassostrea*), pectinids (*Zygochlamys*), muricids (*Trophon*, *Hadriania*), epitoniids (*Cirsotrema*), among mollusks, together with brachiopods, bryozoans, regular and irregular echinoids, asteroids, and balanids. Oysters, represented by *Crassostrea*, are very conspicuous, appearing in vast numbers in many oyster beds at different localities and seem to have been a dominant element of the fauna right up to the Late Miocene. These faunas lived in a temperate shallow nearshore sea.

In the San Jorge basin, Paredes et al. (2014) described a subsurface lithostratigraphic unit (El Huemul formation) underlying marine Miocene sediments. Based on palynological content, they restricted this unit to the Late Eocene/Early Oligocene transition. There are no outcrops of this unit, and fossil content other than palynomorphs has not been identified.

Miocene

Sea-flooding during the Miocene was extensive in the southern part of South America, and vast areas of Argentina were covered by South Atlantic waters at different moments. Marine or marginally marine conditions prevailed in great areas of Patagonia and the Chaco plains, right up to the foothills of the Andes. This high sea level and the changing climate during this epoch brought about important environmental changes reflected in the sedimentology and faunal composition of the rocks deposited then. These rocks contain the richest and best-preserved faunas of the entire Cenozoic in Patagonia, and for this reason these have been the best-known faunas ever since first described by d'Orbigny (1834–1847) and Sowerby (1846). Three main pulses can be recognized, occurring at different places and moments during the Miocene. Each one includes fossil assemblages that differ in their composition and paleoecological requirements.

Early Miocene

The Early Miocene sea in Patagonia covered northern Tierra del Fuego and most of Santa Cruz south and west of the Deseado massif (Fig. 4), reaching as far west as Argentino lake and Magallanes in Chile. To the north, it occupied narrowing embayment that reached up to Buenos Aires lake. Exposures of the lithostratigraphic units deposited by this transgression appear along the foothills of the Andes, in northern Tierra del Fuego and in Santa Cruz, and along the coast all the way up to Río Negro. The different paleogeographic and paleoecological settings at the localities affected by this transgression result in great variations in faunal composition and taphonomic characteristics of the faunas involved. In western Santa Cruz, a more tectonically disturbed area, the preservation of fossils is never as good as in those contained in some of the units exposed along the coast. The faunas from the western areas include many taxa in common with those in the coastal outcrops. Yet, preservation differences may be hiding the real situation, as in this area the presence of aragonitic shells is uncommon. It was a shallow sea representing the greatest extent of the early Miocene transgression in the region. The faunas now include a lower percentage of Paleoaustral taxa, with an increase in taxa occurring in southern South America and other circum-Antarctic regions formerly related to the Weddelian province (Beu et al. 1997). The final opening of Drake passage and the full establishment of the Antarctic Circumpolar current and its climatic and paleoceanographic consequences also brought about changes in the faunas. These changes are better appreciated in outcrops along the coast. Because of the excellent preservation of aragonitic and calcitic shells here, the faunal diversity is unusually high and includes over 160 taxa, many of which had gone unnoticed because of their small size. The occurrence of genera occurring in these early Miocene deposits that appear in rocks of the same age or older in other parts of the southern continents, such as Antarctica, New Zealand, and Subantarctic islands, suggests the existence of migrant taxa that somehow – possibly rafting – arrived in South America from New Zealand during the Miocene, surely favored by the newly established paleocurrent patterns triggered by the opening of Drake passage or, alternatively, across a West Antarctic seaway (Casadio et al. 2010).

The faunas contained in the units exposed along the coast (mainly the Monte León formation) reveal temperate conditions and are characterized by a great taxonomic diversity including gastropods, bivalves, scaphopods, polychaetes, corals, bryozoans, brachiopods, balanids, decapods, and echinoderms. Because of the rich fossil beds with excellently preserved specimens, this fauna has drawn attention of malacologists and paleontologists for almost two centuries, rendering it one of the better known – from a taxonomic point of view – in the region (Ihering 1907, 1914; Griffin and Pastorino 2005; Pastorino and Griffin 2019, among others). Apart from the high proportion of taxa typical to the southern hemisphere (e.g., *Pseudoportlandia*, *Cyclochlamys*, *Lissarca*, *Neopanis*, *Spissatella*, and *Cyamomactra* among bivalves and *Antizafra*, *Antimelatoma*, *Fusiguraleus*, *Xymene*, *Xymenella*, and *Zeadmete* among gastropods), it also contains a few Paleoaustral taxa (*Pteromyrtea*, *Lahillia*, *Perissodonta, Sigapatella*) and a small percentage of Tethyan elements (*Bathytormus*, *Darwinicardia*, *Parinomya*), and yet others that show Caribbean/North American affinities (*Cidarina*, *Cerithioderma*). In addition, it carries a high number of cosmopolitan and endemic taxa too. An example of the latter is *Neoinoceramus*, a rare genus only found in the Early Miocene of the southern coast of the San Jorge gulf and very poorly represented in the Pueyrredón lake area (El Chacay formation).

To the north of the Deseado massif, the Early Miocene transgression was not quite as extensive. Yet, outcrops of rocks originated by this transgression occur along the coast of the San Jorge gulf up to Comodoro Rivadavia, where they have been recorded in the lower part of the Chenque formation of Bellosi (1990). They reappear near Trelew and in the environs of Puerto Madryn, in northeastern Chubut.

Middle Miocene

During the Middle Miocene, marine conditions persisted mainly in the San Jorge basin, north of the Deseado massif (Fig. 4), where it deposited sediments containing a less diverse fauna than that of the Early Miocene (Camacho and Fernández 1956). Exposures of these rocks occur along the coast of the San Jorge gulf up to near the town of Camarones and are included in the upper part of the Chenque formation (Bellosi 1990; Paredes 2002; Cuitiño et al. 2015a, b). Also, it may be possible that rocks of this age exposed in the environs of Trelew – in northeastern Chubut province – and in the Gran Bajo del Gualicho, in eastern Río Negro province, not far from the city of San Antonio Oeste (Reichler 2010), could have originated during the same transgressive event. The fauna shows a different character from the Early Miocene faunas. Many of the taxa common in the Early Miocene beds have not been recorded here, and new warmwater elements with a Caribbean affinity (Woodring 1982) appear for the first time. Such is the case, among bivalves, of *Torcula*, *Amusium*, *Nodipecten*, and *Ckaraosippur* and, among gastropods, *Profundimitra*, *Sconsia*, *Argenthina*, and *Antinioche*.

Late Miocene

A third Miocene transgressive pulse occurred during the Late Miocene. This was the greatest flooding to affect this part of the continent (Fig. 4). However, in Patagonia, it covered only the northern areas, as its greatest extent was northward and westward over the Chaco-Pampean plain up to the foothills of the Andes in western and northwestern Argentina. This shallow epeiric sea is represented by isolated outcrops occurring along the Paraná river in Entre Ríos province, some marginal marine deposits in western Argentina and richly fossiliferous beds in the Valdés peninsula area and the northern coast of the San Matías gulf. It also appears exposed in eastern Río Negro province and possible westward into the Neuquén basin, where Miocene forams have been recorded at Bajada del Jagüel (Náñez and Malumián 2019). Equivalent rocks also outcrop in Uruguay, near the coast of the Río de la Plata.

In the Valdés peninsula area, this transgression is represented by rocks with diverse molluscan assemblages, indicating shallowing conditions toward the top of the sections. The fossil assemblages include elements with a Caribbean origin and are quite different from fossil assemblages in earlier rocks (del Río 1988, 1990, 1992, 1994). The influx of warm water into this area and the faunal changes allow the recognition of distinct malacological provinces (Martínez and del Río 2002). The shared taxa with those in the outcrops in Uruguay (Camacho formation) and Entre Ríos (Paraná formation) leave no doubt as to their widespread distribution in this extensive sea. The Puerto Madryn formation, exposed in Valdés peninsula and in the environs of Puerto Madryn and Trelew, is rich in mollusks, bryozoans, brachiopods, balanids, decapods, and echinoderms. It also includes corals and other minor groups. Among the most common taxa are the very abundant pectinids such as *Aequipecten*, *Amusium*, *Leopecten*, and *Moirechlamys*, together with other bivalves among which we note *Anadara*, *Perna*, *Chione*, *Madrynomya*, *Chama*, *Dinocardium*, *Eucallista*, and *Polymesoda*. The latest Miocene saw the demise of the giant species of *Crassostrea*. The diverse fauna of gastropods includes genera such as *Epitonium*, *Calliostoma*, *Valdesia*, *Tegula*, *Glossaulax*, *Notocochlis*, *Odontocymbiola*, and *Trophon*, among many other (del Río 1985; Brunet 1995, 1997; Griffin and Pastorino 2005, among others).

In the Austral basin, there is only one locality in which a Late Miocene fauna was found. This is Fairweather cape, at the mouth of the Gallegos river near the city of Río Gallegos. This outcrop consists of a thin bed of loose sandstone overlying the continental Early Miocene Santa Cruz formation, renowned for its diverse vertebrate fauna. The marine beds contain an impoverished fauna of brachiopods, pectinids (*Chlamys*), oysters (*Crassostrea*), and gastropods (*Trophon*). Shells dated provided a Tortonian age for this deposit (del Río et al. 2013), congruent with ages from beds further north in Valdés peninsula and Entre Ríos.

Pliocene

A general cooling trend in the oceans that began in the Late Miocene (Herbert et al. 2016) led to the establishment of conditions currently prevailing. However, a paleontological record of this marine cooling has not been adequately preserved in Patagonia. Pliocene rocks are extremely rare in this region, where they are restricted to two localities in Santa Cruz, i.e., the coastal cliff at Estancia Makenke, south of Puerto San Julián, and at Sierra Laciar, west of Puerto Deseado (Fig. 4). They contain a fauna including oysters, pectinids, carditids, muricids, and volutids. The shells are included in a loose conglomerate, possibly reworked by Quaternary fluvial systems removing the Pliocene sediments, but not the shells that were dated as early Pliocene (Zanclean) by del Río et al. (2013).

Climatic Change: A Fauna Turnover in the Cenozoic

The pre-Maastrichtian marine faunas in Patagonia reflect the then prevailing climatic "hothouse" conditions and the changing paleogeographic pattern of the southern continents from the initial opening of the Atlantic ocean until the final breakup of Gondwana (Fig. 5). While many taxa were endemic, a large proportion of them shows Tethyan affinities, especially in the Neuquén basin, at that time connected to the Pacific ocean (Aguirre-Urreta et al. 2008). Coeval with the global cooling that occurred during the Maastrichtian, several cool-water taxa that originated in the shelf areas of the continental masses surrounding Antarctica (which were at least

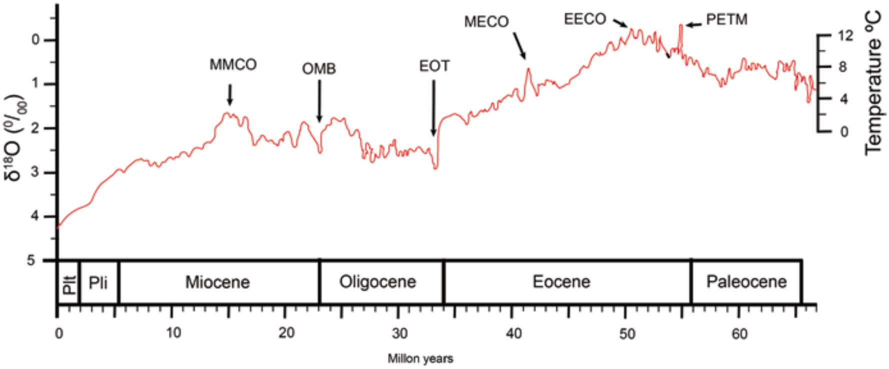

Fig. 5 Cenozoic climatic evolution modified from Mudelsee et al. (2014). References: *MMCO* Mid-Miocene Climatic Optimum, *OMB* Oligocene-Miocene Boundary, *EOT* Eocene-Oligocene transition, *MECO* Mid-Eocene Climatic Optimum, *EECO* Early Eocene Climatic Optimum, *PETM* Paleocene-Eocene Thermal Maximum, *Plt* Pleistocene, *Pli* Pliocene

partially connected) then underwent a northward expansion, even into the Neuquén basin, by then openly connected to the Atlantic ocean and already isolated from Pacific influence. These taxa endemic to the southern cool-water seas were used to describe the Weddellian province (Zinsmeister 1979). Many of them were also known as "paleoaustral" (Fleming 1963), and some of them survived well into the Cenozoic. Examples of these are *Lahillia*, *Austrotrigonia*, *Austroaporrhais*, and Struthiolariidae.

The Cenozoic witnessed a general cooling trend until the present conditions (Fig. 5) (Mudelsee et al. 2014). Yet, this general trend was not uniform and is marked by warmer water events and sudden drops and subsequent recovery of water temperature. A detailed in-depth account of the composition of the Cenozoic faunas of Patagonia and their relation to these changes was published by del Río (2021). Here we offer a brief summary of these changes, and we refer to that contribution for more specific information.

Around the Cretaceous/Paleocene boundary, temperature began increasing, with two peaks during the Danian and a much clearly marked increase at the end of the Paleocene known as the Paleocene-Eocene Thermal Maximum (PETM). With minor fluctuations, water temperature continued to rise until the Middle Eocene Climatic Optimum (MECO). During the Paleocene, faunas in the Austral basin still maintained a Weddellian character, with taxa such as *Lahillia* and Struthiolariids commonly found in deposits of that age, in northern Patagonia, i.e., the Neuquén basin, the immigration of tropical or subtropical taxa such *Bathytormus*, *Gryphaeostrea*, and *Phygraea* (among others) became evident (Fig. 5).

The restricted Middle Eocene faunas include taxa with a paleoaustral origin (e.g., *Australoneilo*, *Darwinices*), other ones with affinities lying in the faunas of the southeastern USA (e.g., *Heteroterma*, *Calorhadia*), yet others with Tethyan affinities (e.g., *Eosolen*, *Electroma*) and the first occurrences of taxa common later during the Miocene (e.g., *Sigapatella*, *Purpurocardia*).

The cooling trend continued for the rest of the Eocene with a swinging pattern during the Oligocene until the sharp drop in temperature occurring at the Oligocene/Miocene boundary (OMB). This event, related to the opening of the Drake Passage and the subsequent establishment of the Antarctic Circumpolar Current, leading to the definite glaciation of Antarctica, caused a sharp change in the character of the fauna, which was mostly replaced by cooler water taxa, well represented in many stratigraphic units deposited by the transgression occurring during the Early Miocene. There are many species described from these units. While the fauna includes paleoaustral, Tethyan, cosmopolitan, and endemic species, the most unique feature is the large proportion showed their first appearance in this part of the continent and named Neogene Southern elements by del Río (2021). Characteristic taxa are *Neopanis*, *Spissatella*, *Austromitra*, and *Retizafra*, among many others.

A recovery of water temperature during the Middle Miocene (Middle Miocene Climatic Optimum – MMCO) saw the demise of many cool-water taxa and the influx of taxa with tropical or subtropical affinities such as *Amusium*, *Nodipecten*, *Antinioche*, *Profundimitra*, and *Sconsia*.

Although still following the general cooling trend, the Late Miocene saw a couple of transient warming events. The well-known Late Miocene fauna includes Paleoaustral, endemic, cosmopolitan, and Neoaustral elements; it shows a strong tropical appearance, with many Caribbean elements. Some of the common Middle Miocene taxa such as *Profundimitra*, *Sconsia*, and *Nodipecten* were replaced by Caribbean elements such as *Chionopsis*, *Hexacorbula*, and *Leopecten*.

Pliocene deposits along the coast of Patagonia are very restricted, but some of the few taxa they contain, such as *Trophon* and the mytilids, already prefigure the character of the fauna currently living on the Argentine shelf (Fig. 5).

Concluding Remarks

The South Atlantic ocean and its surrounding land masses show a complex geological history, which is also reflected in the faunal content of the marine sediments deposited in different basins developed along the opening ocean. The faunas, besides reflecting a general cooling after the high temperatures recorded in Late Cretaceous rocks, suffered fluctuating changes accompanying changes in climatic and paleoceanographic conditions along the Cenozoic. The ongoing process of understanding these changes requires a better appreciation of the present conditions and their bearing on the distribution of taxa with fossil representatives. This should allow a clearer picture of the history of the different faunas involved and the factors linked to their geographic and stratigraphic distribution. This, in turn, should bring about insights into the characteristics of the faunas currently living along the coasts of the South Atlantic.

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Part II
Biodiversity and Ecological Interactions in Coastal Patagonia

Global Change Effects on Plankton from Atlantic Patagonian Coastal Waters: The Role of Interacting Drivers

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Introduction

Since Charles Keeling's first records at Mauna Loa, showing the continuous increase of atmospheric carbon dioxide (CO_2) concentration (Keeling et al. 1976), other global change-related environmental drivers have drawn attention on how they could affect organisms and ecosystems in the future (Bopp et al. 2013, Frölicher et al. 2016). Indeed, studies on the impact of increased ultraviolet radiation B (UV-B, 280–315 nm), as a consequence of reduced ozone levels, especially over Antarctica (i.e., the ozone "hole," Farman et al. 1985), gained much significance all over the World. The atmospheric variables are interrelated in complex ways, and, for example, the warming of the troposphere results in a decrease of temperature in the stratosphere, affecting the ozone layer in such a way that it is uncertain to predict when it will reach its pre-1960 levels again (IPCC 2013, 2019). There is no doubt that increases of CO_2 together with other "greenhouse gases" have resulted in acidification and warming of water bodies, both freshwater and marine (IPCC 2013). Warming, in turn, results in stratification of the water column, but increases in wind speed tend to counteract it (Häder et al. 2014). Not only have human-derived activities directly modified the climate (e.g., through emissions), but also fast-growing human populations and overall globalization have altered ecosystems, due to increasing use and/or pollution of terrestrial-aquatic systems. Undoubtedly, significant changes have occurred in the Earth's system due to anthropogenic influence, with important consequences at biological and socioeconomic levels (Steffen et al. 2004), leading to the idea that a new era has started, i.e., the Anthropocene (Crutzen 2002).

Studies assessing the impact of global change have been carried out in Patagonian coastal marine systems of Argentina since the 1990s (e.g., reviews by Helbling et al. 2005; Gonçalves et al. 2010; Kopprio et al. 2015), focusing on plankton because of their key role in regulating biogeochemical cycles, controlling the sea-surface-atmosphere exchange and the structure and functioning of the entire marine biome. The ecological and economical importance of plankton – and particularly of phytoplankton in coastal Atlantic Patagonia – is well known, as they sustain highly productive fisheries (e.g., Argentine hake and Patagonian shrimp and shortfin squid, among others; see Narvarte et al., this volume). In addition, phytoplankton, via photosynthesis, drives the uptake of large amounts of atmospheric CO_2 (Bianchi et al. 2005, 2009; Kahl 2018), while zooplankton grazing counteracts this uptake (Steinberg and Landry 2017).

The coastal Patagonian region has particular characteristics, in terms of geomorphological and oceanographic features, climatology, and anthropogenic activity, that shape and modulate the responses of plankton to global change. The coastline constitutes varied habitats not only in terms of size and shape but also as protection against rough weather conditions (e.g., wind, rain). These geographic features also condition directly or indirectly the underwater light field and regulate the anthropogenic influence on water bodies (see Saraceno et al., this volume). For example, the large San Jorge gulf (Chubut and Santa Cruz provinces) has high levels of water

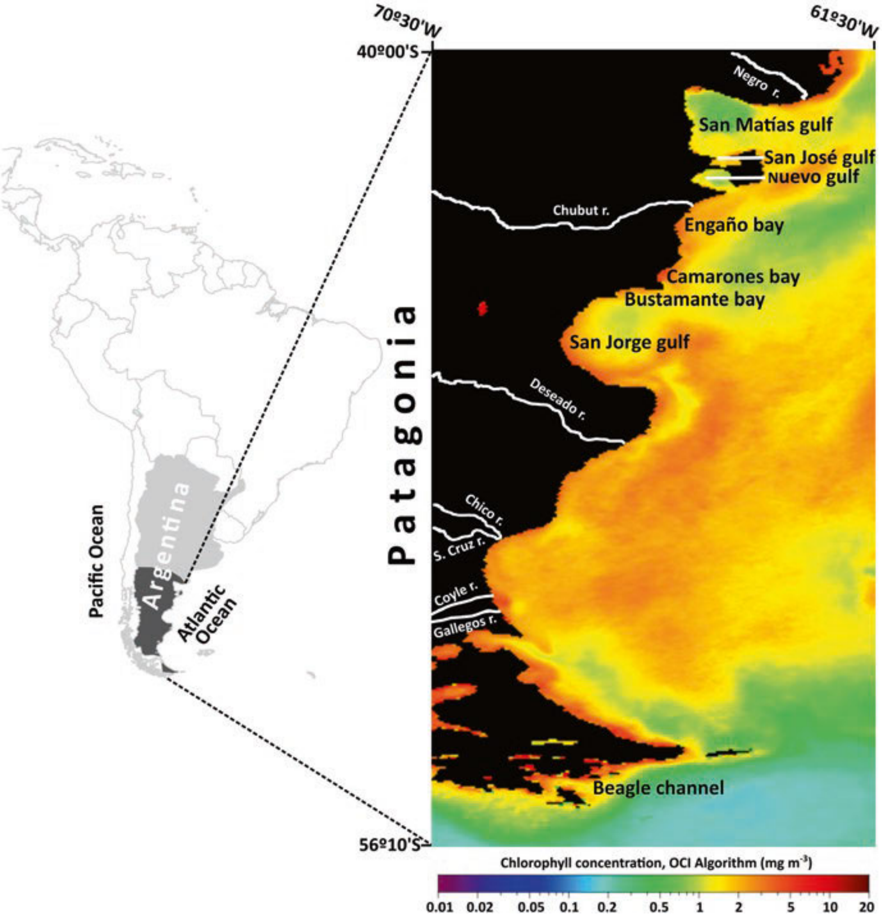


Fig. 1 The map of South America with an enlargement of the coastal Patagonian area of the SWAO, showing the main gulfs and bays. Satellite surface chlorophyll *a* (Chl *a*) distribution during austral winter is shown, as averaged between 2002 and 2019 (8-day area-averaged data were extracted from NASA Earth database using Giovanni v.4.34, and MODIS-Aqua Sensor with 4-km resolution). The main rivers discharging in the SWAO are indicated

exchange, whereas smaller gulfs such as Nuevo and San José (Chubut province) are enclosed sites (Fig. 1) that have lower water renewal rates. Farther South, the Beagle channel is a drowned glacial valley that connects the Pacific and the Atlantic oceans through the Tierra del Fuego island in the southern tip of South America; also, the Navarino and Tierra del Fuego islands act as barriers, giving the Beagle channel the character of a semi-enclosed water body. Oceanographic features such as marine fronts or different water masses (see Saraceno et al., this volume) have intrinsic characteristics (e.g., temperature, salinity, or stability of the water column) that also modulate the distribution and abundance of many planktonic organisms in coastal Patagonia. Few rivers drain in the coastal areas of the Atlantic ocean (Fig. 1; Depetris et al. 2005), but they have a great relevance for the growth of plankton, as they supply continuous amounts of freshwater and terrigenous materials via runoff into estuarine areas. The Negro river supplies the highest discharges (ca. 860 $m^3 s^{-1}$), whereas the Deseado and Coyle rivers have the lowest (ca. 5 $m^3 s^{-1}$) (Depetris et al. 2005). Thus, different types of environments (in terms of turbidity) can be found in coastal Patagonian waters, ranging from clear, open waters, i.e., the large San Jorge gulf, with attenuation coefficients (k_{PAR}) as low as 0.16 m^{-1} at Bustamante bay (Helbling et al. 2001), to systems with large inputs of terrigenous materials from riverine origin (e.g., Engaño bay) that yield values of $k_{PAR} > 4\ m^{-1}$ (Helbling et al. 2010). As for the climatology, one interesting aspect of Patagonia refers to the presence of strong winds, mainly from the west (see Pessacg et al., this volume), especially during spring and summer (Villafañe et al. 2004; Helbling et al. 2005; Bermejo et al. 2018). Also, coastal Patagonia is generally considered a dry and arid region (Garreaud et al. 2013); however, extreme rainfall events are rather common at local scales, with great impacts in coastal cities (Bilmes et al. 2016; Kaless et al. 2019) or at the lower valley of the Chubut river (Vizzo et al. 2021). Patagonia has a very low population density (< 2 inh. km^{-2}, Population Census 2010, INDEC, https://www.indec.gob.ar); however, the presence of several cities along the coast (e.g., Comodoro Rivadavia, Ushuaia, Río Grande, Puerto Madryn, San Antonio Oeste) or on the margin of rivers (e.g., Viedma, Rawson, Trelew, Río Gallegos) results in important anthropogenic influence that directly affects the coastal ecosystem.

Undoubtedly these features, together with a wide range of biotic and abiotic characteristics, make Patagonia a particularly interesting site to evaluate the effects of global change. Thus, in this chapter, we will present our perspective about how global change drivers are affecting plankton (bacterio-, phyto-, mesozoo-, and meroplankton) from coastal ecosystems of Patagonia, using key studies and recent experiments/observations as examples.

Global Change Drivers in the Patagonian Coastal Ecosystem

Global change is a complex phenomenon in which several interplaying drivers are modified directly or indirectly by anthropogenic activity (Steffen et al. 2004; IPCC 2013), affecting in diverse ways the structure and functioning of ecosystems. Although there are clear worldwide trends of global change (e.g., warming, acidification), there is much variability at regional levels, as some patterns are the result of atmospheric circulation and extent of anthropogenic activities. Some drivers gain special importance in Patagonia (e.g., Kopprio et al. 2015); thus, in the following paragraphs, we will describe the interplay among them which are specific for the area, focusing mostly on those relevant for understanding the responses of plankton to global change (Fig. 2).

Solar radiation provides the energy that fuels photosynthesis; however, in order to be converted to bioenergy (i.e., carbohydrates), it needs to be absorbed first by phytoplankton. The absorption depends on physical factors such as the position of

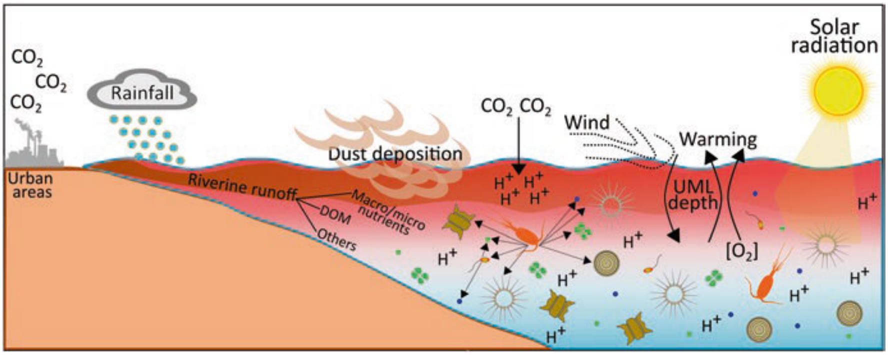


Fig. 2 Graphical scheme showing the main environmental pressures derived from global change (including those of anthropogenic origin) affecting coastal aquatic ecosystems and their plankton communities

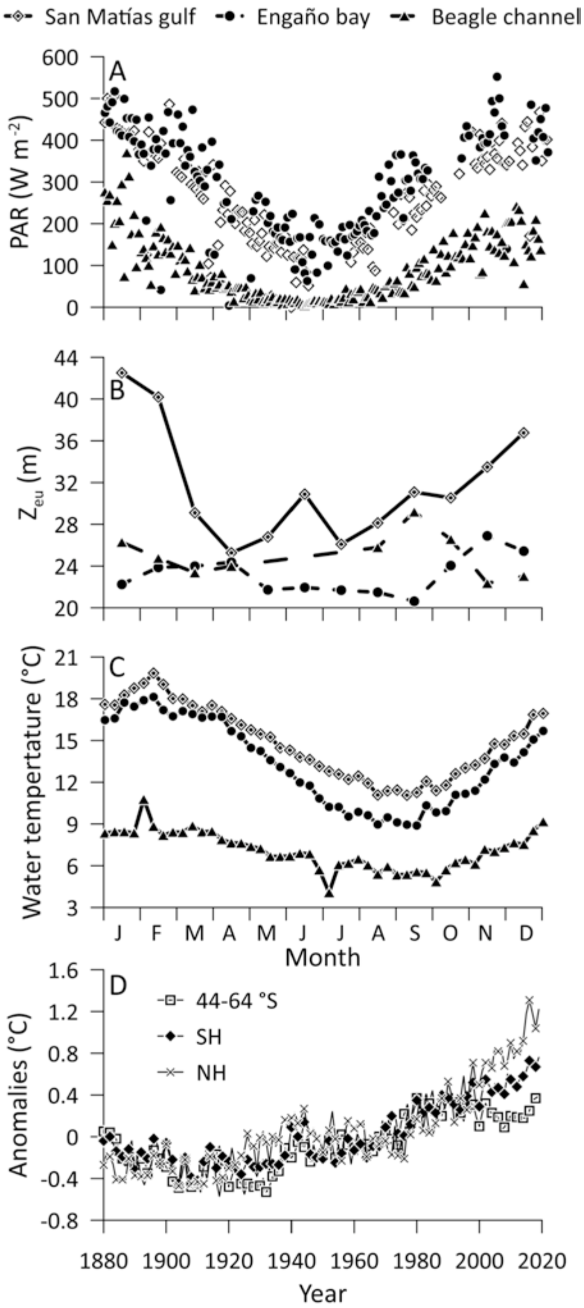
cells (which is a function of the upper mixed layer – UML – depth) and the attenuation of solar radiation in the water column, which, in turn, is related (among other factors) to dust deposition and riverine input of terrigenous materials, including dissolved organic matter (DOM) (Kirk 1994). The absorption is also influenced by the amount of organisms and particles and the concentration of photosynthetic pigments. Another driver of special importance in coastal areas is wind stress, which tends to deepen the UML; however, temperature, an opposing force, tends to shoal it (Gao et al. 2012). Stratification can be also the result of local inputs of freshwater due to glacial meltwater (Randelhoff et al. 2017). The changes in the UML depth will result in a different exposure of organisms to solar radiation, affecting their light history (i.e., their acclimation to low- or high-light levels) and modifying their circulation time within the UML, which conditions the effectiveness of photodamage repair mechanisms.

Coastal areas are also affected by changes in precipitation patterns, e.g., increases in the frequency of extreme rainfall events which will result in more riverine runoff, with higher inputs of inorganic nutrients (e.g., sewage discharges, agriculture or industrial activities wastes) and DOM (Häder et al. 2020; Vizzo et al. 2021). Instead, dryer conditions at certain periods of the year, together with strong winds, favor the input of atmospheric dust (e.g., Patagonian dust, volcanic dust) to coastal water bodies. Thus, and although wind, rainfall, and sewage discharges will result in the attenuation of solar radiation in the water column (implying less energy for photosynthesis), they are also bringing macro- (e.g., phosphorus, nitrogen) and micronutrients (e.g., iron) for growth (Rabalais et al. 2009; Jickells and Moore 2015). Another essential driver that fuels photosynthesis is CO_2, which is incorporated by phytoplankton, increasing the pH of the water; by contrast respiration tends to decrease the pH. Thus, the increase of atmospheric CO_2 alters this balance, and more CO_2 exchange occurs between the air-sea interphase, and the net result is a general decrease of pH in the ocean, leading to acidification (IPCC 2013). Additionally, increased stratification could lead to changes of ocean ventilation and reduce oxygenation due to both increased temperature (i.e., global warming) and respiration and remineralization (Shepherd et al. 2017).

To understand the impact of global change on plankton from Patagonian coastal waters, it is necessary to consider the changes of the different drivers and variables along the year as well as their latitudinal variations; some of the main drivers (variables) of photosynthesis are shown in Fig. 3. Photosynthetically active radiation (PAR, 400–700 nm) has a clear seasonality and follows a characteristic U shape with minimal values in winter and maximal in summer (Fig. 3A). As expected, PAR also displays spatial variability, with irradiance being lower in subpolar than in temperate latitudes at the same time of the year. In coastal sites of Patagonia, maximal noon solar PAR values range from ca. 550 to 350 W m^{-2} between northern (San Matías gulf and Engaño bay) and southern latitudes (Beagle channel), respectively, during summer, whereas in winter this range is 200 to 20 Wm^{-2} (Fig. 3A). The daily variations observed in PAR are due to the differences in cloud cover that are strong absorbers of solar radiation. Ultraviolet radiation (UVR, 280–400 nm) follows a similar pattern, with ranges between 80 and 25 Wm^{-2} (summer) and 25 and 4 W m^{-2} (winter), for northern and southern latitudes, respectively (Orce and Helbling 1997; Diaz et al. 2006). Incident solar radiation is also affected by the presence of low-ozone concentration air masses originating in the Antarctic polar vortex that reach northern Patagonia (Orce and Helbling 1997; Diaz et al. 2006) and can be traced as far as southern latitudes of Brazil (Bresciani et al. 2018). This results in relative increases of UV-B levels over Patagonia during springtime, but these low-ozone events, however, are sporadic and last only a few days (Helbling et al. 2005). The attenuation of solar radiation in the water column, due to the presence of different absorbers, results in different depths of the euphotic zone (Z_{eu}, the zone in which photosynthesis exceeds respiration). In Patagonian coastal waters, Z_{eu} ranges between 42 and 20 m, in San Matías gulf and Engaño bay, respectively, whereas the Beagle channel presents intermediate values (~25 m; Fig. 3B). Coastal waters of the Southwest Atlantic Ocean (SWAO) are also characterized by seasonal changes of surface temperature, with broad latitudinal ranges over the year along Patagonia, having mean summertime monthly values of ~19 °C in the San Matías gulf and 9 °C in the Beagle channel, and values <12 and 6 °C, respectively, during winter (Fig. 3C). These actual seasonal patterns are the result of an overall increase in temperatures that at high latitudes in the southern hemisphere (44–64°S) resulted in a change of ~0.8 °C since ca. 1930. These anomalies follow the same increase as those for the whole southern and northern hemispheres until ca. the year 2000; then, the anomaly rate for the 44–64°S area decreased when compared to the southern and northern hemispheres (Fig. 3D).

There is also evidence that acidification mediated by rising atmospheric CO_2 concentrations is already occurring in Patagonia since the Industrial Revolution at an annual rate of 0.0010 pH units yr^{-1} on the shelf-break (Orselli et al. 2018). In coastal systems (e.g., estuaries), however, there are more complex interactions among several abiotic factors (inorganic nutrients, DOM, etc.) that can affect the balance between primary production and respiration and hence the pH exchange rates (Duarte et al. 2013; Villafañe et al. 2015). For example, in specific areas such

Fig. 3 Seasonal variations of (**A**) photosynthetically active radiation (PAR, 400–700 nm); (**B**) depth of the euphotic zone; and (**C**) sea surface water temperature along the year for three sites, San Matías gulf (◊), Engaño bay (●), and Beagle channel (▲) (see Fig. 1 for location). Data in B and C were extracted from NASA Earth database using Giovanni v.4.34. MODIS-Aqua Sensor, with 4-km resolution. (**D**) Mean annual temperature anomalies for the Northern (NH) and Southern hemispheres (SH) and for 44–64°S, from 1880 to 2019. Data were extracted from NASA-GISS surface temperature analysis (GISTEMP v.4) with a 2° × 2° grid resolution



as those dominated by macrophyte/saltmarsh communities, which are important CO_2 sink areas, pH and oxygen supply to the water can increase, thereby locally reducing processes of acidification and deoxygenation (Duarte et al. 2013, 2017; Sondak et al. 2017). Overall, the predicted trends of acidification are scarcely known for coastal Patagonian waters, but a recent report by Jiang et al. (2019) shows that pH has decreased about 0.14 units over this area between the years 1770 and 2000. Moreover, it shows moderate/high Revelle factor values (i.e., a proxy of the ocean's buffer capacity for the carbonate system), indicating that this ecosystem has low buffering capacity, and therefore, it is more susceptible to faster changes in the partial pressure of CO_2 than other coastal ecosystems worldwide.

Patagonia had experienced high human population growth (ca. 21% between 2001 and 2010; Gil et al. 2019) with a concomitant increase in pollution due to urban, industrial, and agricultural activities. Pollution is evidenced in different ways (Gil et al. 2019), but the discharges of crude sewage or byproducts of fishery industry, and the inputs of nutrients from agriculture through river runoff, are especially relevant for plankton, as they may lead to eutrophication (Rabalais et al. 2009). Indeed, eutrophication has been determined in several sites of coastal Patagonia (Esteves et al. 2000; Gil et al. 2011). For example, significantly higher nutrients (ca. double for nitrogen and phosphorus) were determined in Engaño bay (Bermejo et al. 2018) during 2015 as compared with a reference period (1986–2014), mainly related to the more intense use of land (i.e., agricultural activities and excessive use of fertilizers; Kopprio et al. 2015) as well as to the dumping of byproducts from fish processing factories located at the mouth of the Chubut river. Other type of pollutants, e.g., oil due to accidental spills (Commendatore and Esteves 2007), also have special significance for plankton because they are known to inhibit various physiological processes, including growth (Broussard et al. 2016).

Spatio - temporal Distribution of Plankton in Patagonian Coastal Environments

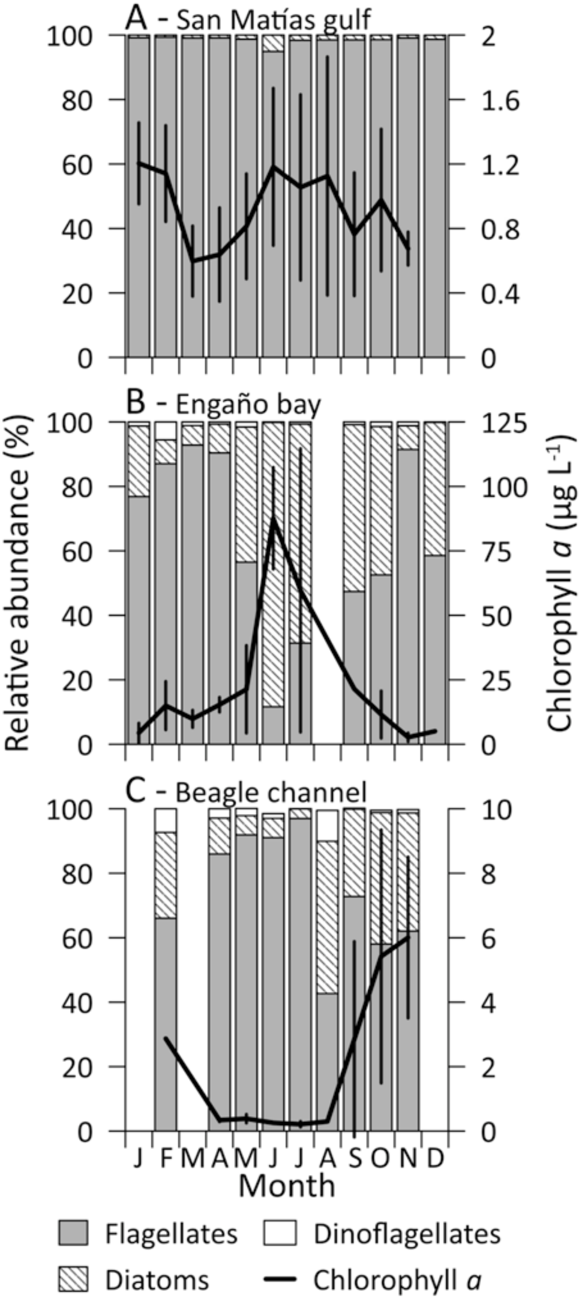
During the last decades, there have been considerable national and international efforts to study plankton abundance and distribution patterns along the SWAO, including coastal Patagonia. There are also many regional studies either as part of long-term monitoring programs or as specific experimental research, but most of them represent a "snapshot" for a particular time of the year or site. In spite of this, some generalizations for the plankton of coastal Patagonia can be made which will be the focus of this section.

The high primary productivity of Patagonia is already well known, when compared to the global ocean (Longhurst et al. 1995; Heileman 2009), especially in coastal areas and over the shelf-break front, the latter considered a "hotspot" (Martinetto et al. 2020). These estimations, based on satellite data, are further validated by field measurements at a regional scale (Lutz et al. 2018). Satellite data have provided essential information on seasonal large-scale patterns of chlorophyll *a* (Chl *a*; see Fig. 1), which is frequently used as a proxy of phytoplankton biomass. Such data, however, should be used cautiously as this parameter only provides information from the upper part of the UML, which often does not represent the distribution of Chl *a* along the euphotic zone (Silsbe and Malkin 2016); additionally, Chl *a* is greatly influenced by the light history and the physiological status of phytoplankton cells. Nevertheless, there is no doubt that coastal Patagonian waters have, in general, much higher Chl *a* values than the open ocean (Marrari et al. 2017), although there is high spatial (Fig. 1) and temporal variability (Fig. 4). For example, in situ measurements in the San Matías gulf showed monthly averaged values <2 μg Chl *a* L^{-1} and a marked dominance of flagellates throughout the year (Fig. 4A). At a southern location, Engaño bay, a recurrent late winter bloom reaching mean monthly values as high as ~90 μg Chl *a* L^{-1}, is dominated by diatoms, mainly *Odontella aurita* and *Thalassiosira* spp. (Villafañe et al. 2004; Bermejo et al. 2018, Fig. 4B). At the Beagle channel, a characteristic bloom (~6 μg Chl *a* L^{-1}) occurs during spring-summer (Fig. 4C), and it is co-dominated by flagellates and diatoms such as *Chaetoceros* spp. (Almandoz et al. 2011). The information about small cell-sized groups (picoplankton, < 2 μm) is very scarce (Villafañe et al. 2008; Guinder et al. 2020; Vizzo et al., unpublished); however, available studies and model outputs show that cyanobacteria (*Prochlorococcus* and *Synechococcus*) and green algae can reach significant abundances, potentially contributing for an important share of phytoplankton productivity along the coast of Patagonia (Flombaum et al. 2013). Model outputs also predicted that these small cells would have a positive response to ocean warming and lower nutrients, increasing their biomass (Flombaum et al. 2020).

Toxic phytoplankton outbreaks, commonly named as red tides, are also typical along the Patagonian coast. In the Río Negro and Chubut provinces, they are mainly due to the dinoflagellate *Alexandrium tamarense*, which is responsible for producing paralytic shellfish poison toxin (Fabro et al. 2017); other toxic dinoflagellates species have also been reported, i.e., *Dinophysis acuminata*, *D. tripos*, and *Prorocentrum lima* (diarrheic shellfish toxins producers, Krock et al. 2018; Sastre et al. 2018). In the Beagle channel, *A. tamarense*, *A. catenella*, and *A. ostenfeldii* are the main contributors to these red tides (Krock et al. 2018; Montoya et al. 2018). Also, dinoflagellates from the genera *Azadinium* and *Amphidoma*, which are known to produce azaspiracids, a group of toxins responsible for diarrheagenic and tumorigenic effects in vertebrates (Krock et al. 2018), were recently identified from the San Jorge gulf to the Beagle channel (Fabro et al. 2019). Finally, potentially toxic diatom species (i.e., amnesic shellfish poisoning – domoic acid) such as *Pseudo-nitzschia* spp. have also been registered along all Patagonian coastal waters (Ferrario et al. 2002; Almandoz et al. 2017; Krock et al. 2018). These toxic outbreaks are of utmost importance as they affect invertebrates of economic interest (i.e., mollusks) or other vertebrates (including humans).

The knowledge of patterns of abundance and distribution of zooplankton is largely biased toward the mesozooplankton fraction (0.2–20 mm). The distribution of some copepod species appears to be largely associated with latitudinal gradients

Fig. 4 Seasonal changes in relative abundance (staked bars) of the main phytoplanktonic groups – diatoms, flagellates, and dinoflagellates – and of in situ surface Chlorophyll *a* (thick solid lines with standard deviation as vertical lines) at (**A**) San Matías gulf (data from Saad unpublished), (**B**) Engaño bay (data from Bermejo et al. 2018), and (**C**) Beagle channel (data from Almandoz et al. 2011); see Fig. 1 for location



(Cepeda et al. 2018), but it also depends on oceanographic features, such as frontal areas, or associated with different water masses. Relatively few annual studies have been published for the coastal Patagonia, but it has been reported that cladocerans are the most conspicuous (and abundant) in the Nuevo gulf (Berasategui et al. 2018). Copepods are generally dominant in the Beagle channel (Berasategui et al. 2018) but with high spatial variability due to anthropogenic influence (Biancalana et al. 2014, 2020; Presta et al. 2020). In Engaño bay, Spinelli et al. (2016) studied the annual cycle of copepods and determined two clear phases associated with environmental conditions and availability of food. Thus, *Calanoides carinatus* dominated when temperature and solar radiation were low and the phytoplankton communities were dominated by diatoms (i.e., autumn/winter). However, *Euterpina acutifrons* dominated under high temperature and solar radiation conditions and when the phytoplankton communities were dominated by flagellates (i.e., spring/summer).

One group of organisms that has received very little attention refers to those that spend only the larval or early stages of their life as part of the plankton, i.e., meroplankton. We compiled information about the spawning period and presence of larvae throughout the year of some ecologically and economically relevant species (Fig. 5). In general, and regardless of location, there is virtually no spawning during late autumn-early winter, with a few exceptions, e.g., the mollusk *Illex argentinus* in the north Patagonian shelf and the echinoderm *Cosmaterias lurida* in the Beagle channel (Fig. 5A). Also, the length of the spawning season is variable, with some species having a relatively larger one (e.g., the different subpopulations of *I. argentinus* in the North Patagonian shelf, *C. lurida* in the Beagle channel, and the crustacean *Leucippa pentagona* in Nuevo gulf), whereas others have a spawning period restricted to a few weeks in autumn (e.g., *C. lurida* in Nuevo gulf) (Fig. 5A). Meroplankton larvae are generally absent during late autumn and early winter (Fig. 5B), and their presence is variable, from several months during late winter, spring, and early summer (e.g., the crustacean *Munida gregaria* in Nuevo gulf), to a couple of months during late summer (e.g., *I. argentinus* in the San José gulf) (Fig. 5B). Other organisms also spend part of their life cycles as components of plankton, such as fishes and benthic macroalgae. For fishes (as well as for planktonic organisms), fronts seem to be a favorable habitat for spawning and nursery; therefore, ichthyoplankton abundance (e.g., anchovy, hake, sandperch) is high in these sites (Fig. 5B, Acha et al. 2018). They also have a different time span for spawning and larvae occurrence, i.e., short periods for *Merlucius hubsii* in the San Matías gulf and *Pseudocerpis semifasciata* in San José gulf, respectively, and longer ones for *P. semifasciata* in north Patagonia and *M. hubsii* in the lower tidal fronts, respectively. Some species of macroalgae present planktonic zoospores, hence contributing to a high share of plankton biomass; for example, *Ulva lactuca* propagules during low tides in San Antonio bay (within the San Matías gulf) and can dominate the whole primary producer community during spring and to a lesser extent in summer (Saad et al. 2019).

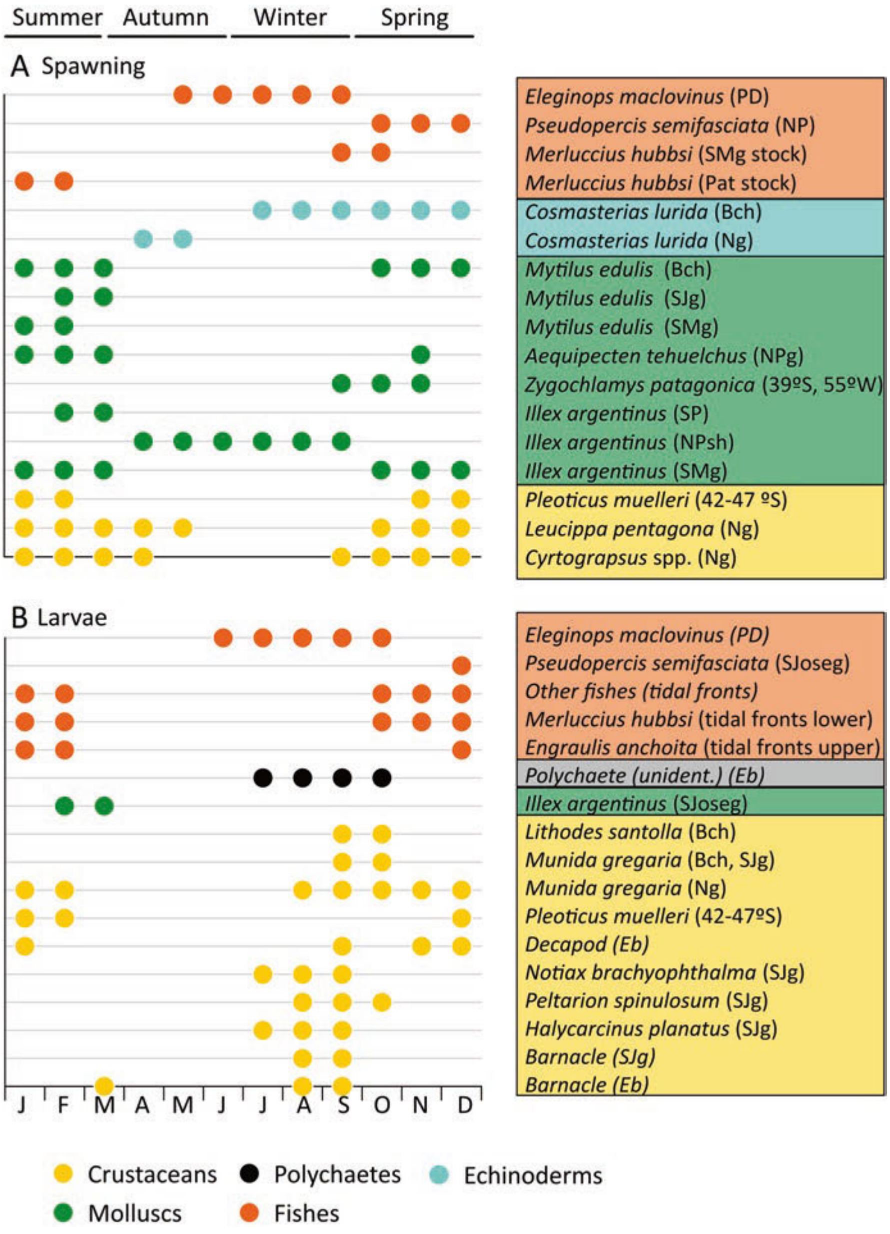


Fig. 5 Spawning period (**A**) and seasonal presence of larvae along the year (**B**) of the main species with meroplanktonic stages in the SWAO. The different taxonomic groups are indicated in different colors, and the abbreviations in brackets denote Puerto Deseado (PD), North Patagonia (NP), San Matías gulf (SMg), Beagle channel (Bch), Nuevo gulf (Ng), San Jorge gulf (SJg), North Patagonian gulfs (NPg), South Patagonia (SP), North Patagonian shelf (NPsh), San José gulf (SJoség), and Engaño bay (Eb). Data from Acha et al. (2018), Campodónico et al. (2008), Cossi

Assessment of the Impact of Global Change Drivers on Plankton

Methodological Aspects and Constraints

Over the past three decades, great efforts have been made to determine the impact of global change drivers on plankton from Patagonia. The large body of literature obtained through experimental work, however, is biased toward phytoplankton, as also observed for the SWAO in general (Valiñas et al. 2018), and indeed, there is scarce information for other groups, such as bacterio-, mero-, or mesozooplankton. Different methodological approaches and time scales have been used, and, as in other sites worldwide, the experimental work initially emphasized the effects of single drivers. Only over the last two decades, studies have considered multi-driver scenarios as normally occurring in nature (Gunderson et al. 2016), with antagonistic and synergistic interactions among variables being the rule, whereas additive effects being less common (Jackson et al. 2016; Villar-Argaiz et al. 2018). However, as the number of drivers increases, the complexity in experimental design and effort, and in the interpretation of the results, increases also (Brennan and Collins 2015). Multivariable studies in Patagonia have been carried out either under factorial (e.g., Cabrerizo et al. 2017), i.e., with the impact of drivers or variables assessed in multiple combinations among them, or cluster approaches (Villafañe et al. 2015), in which all variables are tested at the same time and together, so that the interaction among them is the net result. Each approach has benefits and limitations: for example, while factorial approaches consider all possible combinations of variables, they require more effort and technical resources, i.e., a larger sample size is needed and is more time-consuming, due to increased number of combinations and replicates (Boyd et al. 2018). Also, and because of the large number of samples, the measurements sometimes are not simultaneous, and thus, the interpretation of the results may be misleading, especially when considering the impact of drivers that vary over short-term scales (e.g., solar radiation, temperature). Cluster experimental approaches that test two (or more) contrasting conditions, i.e., present vs. a simulated future scenario, provide a more realistic information about the combined effect of all drivers, as they occur in nature, but do not discriminate the extent of the individual effects.

The predictions of global change effects on plankton also depend on the temporal scale used in experimentation; therefore, both short- (hours) and long-term (days) studies are needed to differentiate, for example, fast and transient responses

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Fig. 5 (continued) et al. (2015), Crespi-Abril (2009, 2014), Dellatorre and Barón (2008), Escriche (2009), Fernández et al. (2012), Glembocki et al. (2015), González (1999), Gosztonyi (1979), Hernández Moresino and Helbling (2010), Haimovici et al. (1998), Lasta and Calvo (1978), Macchi et al. (1995), Marcoval et al. (2018), Narvarte and Kroeck (2002), Narvarte (2001), Ocampo Reinaldo et al. (2013), Oehrens Kissner and Kroeck (2006), Pájaro et al. (2005), Pastor-de-Ward et al. (2007), Sar et al. (2018), Spinelli et al. (2016), Tortorelli (1987), Varisco (2013), Venerus et al. (2005, 2008), Vinuesa et al. (1985)

derived from acclimation, from those obtained over evolutionary scales (Collins et al. 2020). Long-term studies also require that the simulation of a future scenario incorporates either a sustained (or single) or a gradual (or intermittent) perturbation (Thornton et al. 2014). Finally, and with a few exceptions, e.g., mesocosm studies (containers of ~100 L of capacity) performed in the Beagle channel (Hernando et al. 2006, Moreau et al. 2014), most studies done in Patagonia have used microcosms (containers of ~10 L capacity) in which only responses at individual or population (or small size community) levels are considered. However, in most of these experiments, species interactions within and among multi-trophic levels are not considered, and thus it is difficult to assess the impact of global change at the ecosystem level (see Valiñas et al., this volume), as top-down or bottom-up effects can be transferred or damped among the interacting organisms.

Studies of Global Change Impacts on Plankton from Patagonia

Bacterioplankton

Few experimental studies have been carried out with natural bacterioplankton communities from Patagonian coastal waters. Manrique et al. (2012), studying the taxonomic composition of bacterial communities of Engaño bay (through analyses of 16S rDNA gene libraries), found that the *Bacteroidetes* group was more abundant in treatments where UV-B was screened out, whereas *Alphaproteobacteria* dominated in samples receiving UV-B. These responses were speculated to be due not only to the species-specific sensitivity to UVR of the bacterial groups (Joux et al. 1999) but also to the differences in bioavailability of DOM (Obernosterer et al. 1999), as well as to the taxonomic structure of phytoplankton (Carrillo et al. 2015) co-occurring with bacteria under the different radiation treatments. Global change-induced effects on bacterioplankton abundance (using flow cytometry) were assessed in mesocosm experiments carried out with natural plankton communities from the Beagle channel exposed to individual and simultaneous increases of temperature (+3 °C) and UV-B (simulating a 60% decrease in stratospheric ozone, Moreau et al. 2014). Only high-temperature treatments resulted in a decrease in bacterial abundance (40% in average), probably caused by predation control due to the increase in the abundance of large ciliates. It was suggested also that changes in the phytoplankton taxonomic composition altered the qualitative and quantitative composition of excreted organic carbon (EOC) released, which may have been less suitable

Fig. 6 (continued) as single drivers, are also shown. Drivers are Solar ultraviolet radiation (UVR), nutrients from atmospheric dust deposition (Nut_D), nutrients from river input (Nut_R). Interactive effects: UVR and nutrients from dust (Int_{UVRxD}), UVR, and nutrient from the river (Int_{UVRxR}). Additive effects: UVR and nutrient from dust (Add_{UVR+D}), UVR, and nutrients for the river (Add_{UVR+R}). Data from Cabrerizo et al. (unpublished) and re-analyzed and re-drawn after Cabrerizo et al. (2018)

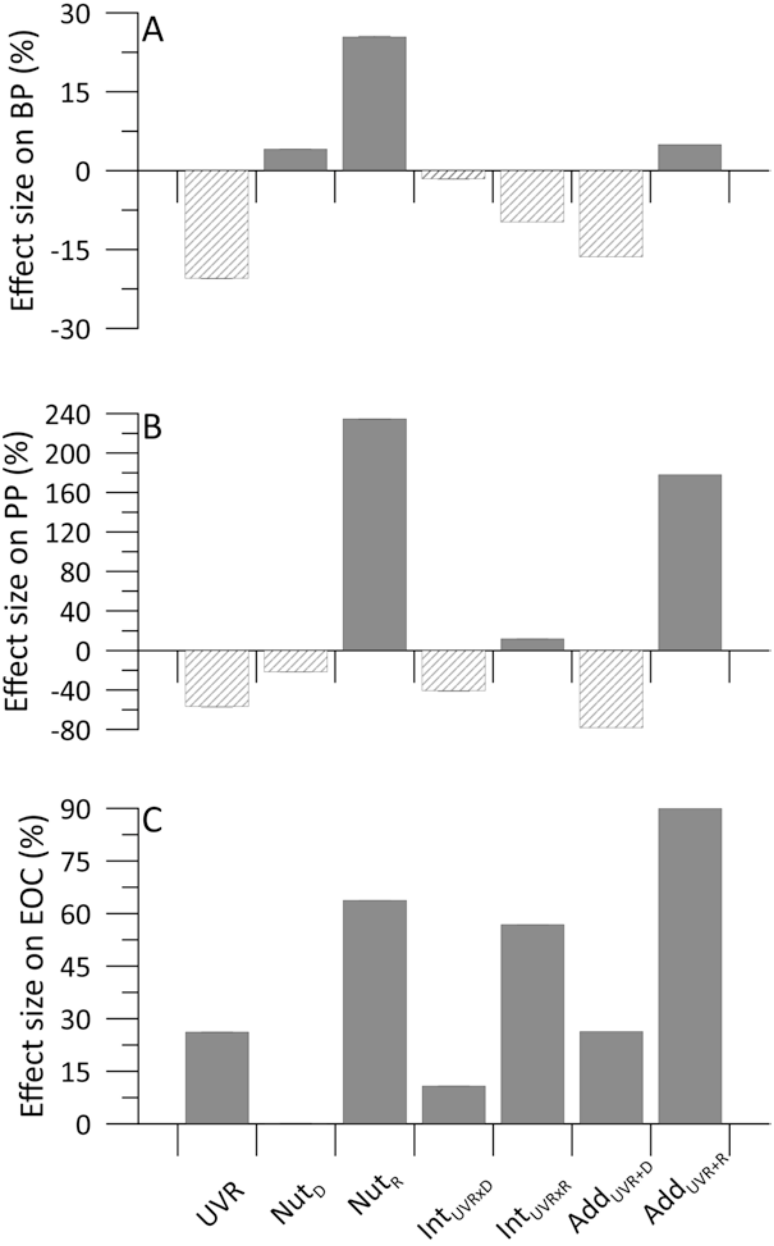

Fig. 6 Mean effect size (±SD) (in %) of single or combined drivers on (**A**) bacterial production (BP), (**B**) phytoplankton primary productivity (PP), and (**C**) phytoplankton-excreted organic carbon (EOC). Negative values indicate a decrease (i.e., inhibition, dashed bars), while positive values indicate an increase (i.e., enhancement, gray bars) of the process involved (effect size = (control – scenario)/control × 100). For comparison, the additive effects of UVR with dust and river inputs,

for the bacteria present within the mesocosms. In this experiment, no UV-B effects were observed, probably because this summer bacterial community was already adapted to high UV-B after the decrease of ozone concentrations which are typical at this high latitude site (Moreau et al. 2014). In studies carried out in Engaño bay, Durán-Romero et al. (2017) found that a simulated future scenario of higher acidification and nutrient inputs favored the growth (determined by flow cytometry analysis) of heterotrophic bacteria, which increased almost threefold over the control. Nevertheless, the growth was still higher in samples in which UVR was excluded (ca. 30% more than the cells exposed to UVR), suggesting that the future scenario was not enough to completely mitigate the UVR effects. The stimulated bacterial growth in the future environmental scenario could be due not only to a direct consequence of higher availability of organic carbon and inorganic nutrients (Baltar et al. 2015) but also to taxonomic changes in the bacterial community due to UVR exposure (Manrique et al. 2012).

Studies carried out in Engaño bay determined the effects of UVR on bacterioplankton production (BP, assessed through ^{3}H-leucine incorporation) under increased acidification and nutrients and found that the sensitivity of this group to UVR changed from an inhibition of 53 and 74% (under the present and future scenarios, respectively) at the beginning to an enhancement >50% in both conditions toward the end of the experiment (Durán-Romero et al. 2017). In another experiment (Cabrerizo et al., unpublished) BP (also assessed through ^{3}H-leucine incorporation) was inhibited by ca. 20% due to UVR, but it was stimulated by 4 and 25% after the inputs of Saharan dust or inorganic nutrients that mimicked aeolian dust deposition or riverine (runoff) events (as single drivers), respectively (Fig. 6A). Both drivers reduced the UVR-induced inhibition on BP (i.e., antagonistic effect), but UVR was still the driver that was responsible for an overall decrease of BP of ca. 2 and 10%, respectively (Fig. 6A). Parts of these responses of bacterioplankton were linked to those of phytoplankton in which the riverine input of nutrients, as a single driver, increased the primary productivity – PP (Fig. 6B; Cabrerizo et al. 2018) and the EOC (Fig. 6C, both estimated using radiocarbon techniques). EOC by phytoplankton is often stimulated under UVR as a mechanism to reduce algal physiological stress (Carrillo et al. 2008).

Phytoplankton

The impact of solar UVR on phytoplankton photosynthesis from Patagonian coastal waters has been assessed using different techniques: (a) oxygen evolution, coming from the water split after the solar energy has been absorbed; (b) measurements of effective photochemical quantum yield (ϕ_{PSII}) and electron transport rate (ETR) of the photosystem II (PSII) during the light phase of the photosynthesis; and (c) carbon incorporation, which represents the production of carbohydrates during the dark phase of the Calvin-Benson-Bassham cycle. While UVR is generally considered a stressor for several processes (e.g., inhibiting photosynthesis or growth), some studies, however, showed that longer wavelengths, mainly ultraviolet

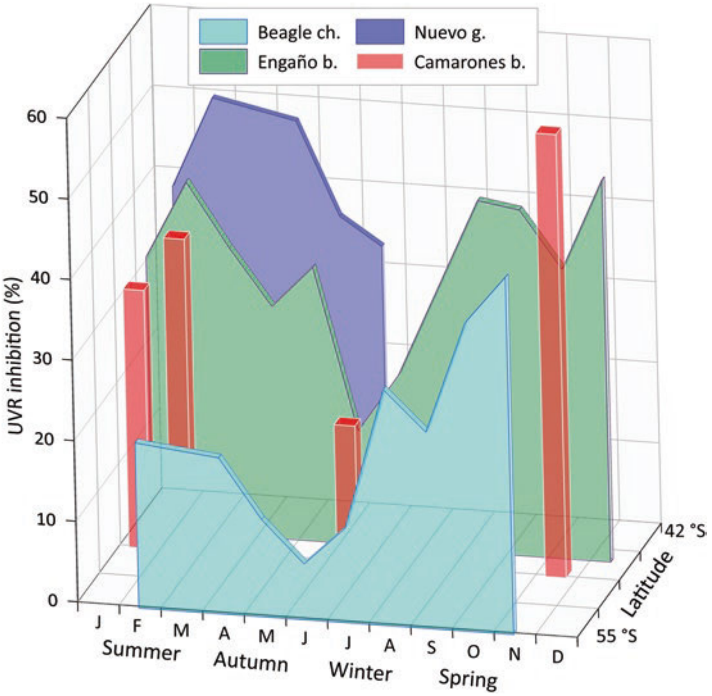

Fig. 7 Short-term inhibition of phytoplankton primary productivity due to solar ultraviolet radiation (UVR) at four sites: Nuevo gulf, Engaño bay, Camarones bay, and Beagle channel in the SWAO (see Fig. 1 for location). Data re-analyzed and re-drawn after Villafañe et al. (2004) (data from Engaño bay, Nuevo gulf, and Camarones bay) and Hernando and Ferreyra 2011 (data from Beagle channel)

radiation A (UV-A, 320–400 nm), can be used as an extra source of solar energy for photosynthesis when PAR levels are low, either due to cloud cover or in a deep UML (Barbieri et al. 2002; Gao et al. 2007) or by fast-mixing derived from strong wind events in surface waters (Helbling et al. 2003). UV-A can also be beneficial to phytoplankton as it has a key role in deoxyribonucleic acid (DNA) repair once the damage has been produced (Buma et al. 2003). The tradeoff which results in a stressful or a beneficial effect strongly depends on the cellular physiological status as well as on the specific sensitivity to UVR, which subsequently can be modified when other global change drivers interact (Brennan and Collins 2015).

We compiled all data available about the effects of UVR on PP (obtained by radiocarbon technique) in coastal Patagonian waters, and we found that across latitudes, similar patterns of UVR-induced inhibition of PP can be determined (Fig. 7). The overall inhibition was greater during spring and summer (ca. 50%) and much lower during winter (< 15%), following the solar radiation curve along the year (Fig. 3). These values, however, represent the worst-case scenario because they were obtained in short-term incubations (few hours); hence, the cells did not have enough time to acclimate to the experimental conditions imposed (see below).

In spite of this clear pattern along the year, some latitudinal variability was observed. These variations are probably related to the particular taxonomic composition of the communities (hence with different sensitivity to UVR) found in these areas, as well as with the sea surface water temperature range between southern and northern latitudes (Fig. 3C). This yield variations in photosynthesis and repair mechanisms because they show strong thermal dependence (Wu et al. 2017).

Engaño bay was used as a model site to evaluate the impact of global change variables on different targets and processes, using different time scales of experimentation. It was found that, in spite of the lower radiation levels typical of the winter, bloom communities dominated by diatoms were comparatively more sensitive to UVR (per unit energy), as assessed through biological weighting functions (BWFs) of PP, than those of the pre- or post-bloom (Villafañe et al. 2004), as was also found in other temporal or seasonal comparisons (Villafañe et al. 2008, Cabrerizo et al. 2017). The higher sensitivity was related not only to the low winter temperatures which restricted repair mechanisms, as observed for the first time in Antarctica (Neale et al. 1998), but also to an increased excitation pressure of the PSII (Maxwell et al. 1995). The short-term UVR × temperature effects on photosynthesis (using daily cycles of ϕ_{PSII}) were synergistic during the bloom and spring time periods, i.e., with temperature increasing the overall UVR-photochemical inhibition, whereas they were antagonistic during the bloom onset, with temperature counteracting inhibitory UVR effects (Villafañe et al. 2013). Also, the combination of UVR × temperature × nutrients resulted in a higher net community production (NCP, assessed through oxygen production) and better PSII performance during the pre-bloom, as compared with the bloom communities (Cabrerizo et al. 2017).

Since plankton do not stay at a fixed depth in the water column, but rather they move in a turbulent environment, they are exposed to fluctuating UVR and PAR regimes. Mid-latitudes, including most of Patagonia, are under the influence of strong westerlies (i.e., the "roaring forties") that condition the UML depth, the position of plankton in the water column and thus, the amount of solar radiation received (Neale et al. 2003). The key role of wind as a shaper of phytoplankton communities in coastal Patagonia was studied by Villafañe et al. (2004) who determined that the calm conditions (almost no wind) characteristic of winter allowed the growth of microplanktonic diatoms within a shallow and stable UML, yielding to a typical bloom. Changes in wind patterns during the year 2015, resulted in a delay of the bloom by almost 2 months, as well as in an altered community (with respect to historical records) dominated by small diatoms (< 20 μm) (Bermejo et al. 2018). The effects of UVR and mixing conditions were also determined in experiments carried out in the Beagle channel (Hernando et al. 2006), resulting in a community initially dominated by flagellates turning into one dominated by diatoms in fixed surface conditions; however, under mixing, flagellates were still the dominant group at the end of exposure. Also, the speed of vertical mixing and the portion of the euphotic zone that was mixed determined the extent of UVR- induced inhibition on PP (Helbling et al. 1994; Barbieri et al. 2002). In Engaño bay, the integrated PP under mixing conditions was ca. 5–20% higher than under static ones during the pre- and post-bloom, while during the bloom, it decreased by ca. 15% (Barbieri et al. 2002).

This study further showed that UVR reduced the integrated PP of post-bloom communities by 11–13% and increased it by 7–12% when 60% and 91% of the euphotic zone were mixed, respectively. The combined impact of solar UVR and vertical mixing on photosynthesis is also cell size dependent (Helbling et al. 2008): larger cells, such as *Prorocentrum micans* suffered little UVR inhibition under different mixing speeds, while smaller ones, such as *Gymnodinium chlorophorum*, experienced an increasing UVR inhibition as the speed of vertical mixing augmented. By contrast, damage to the DNA molecule, evaluated as the production of cyclobutane pyrimidine dimers (CPDs, mainly thymine dimers T<>T), was not altered in any case (Helbling et al. 2008). However, significant amounts of CPDs, ca. 600 T<>T per 10^6 nucleotides, were determined in a summer phytoplankton community of Bustamante bay at the surface of the water column (Buma et al. 2001; Helbling et al. 2001), but the damage disappeared relatively fast with depth as solar radiation attenuated. The amount of CPDs was higher than that determined in tropical latitudes (Buma et al. 2003), probably due to a rapid accumulation during the day, tied with a minor photoreactivation by PAR or UV-A wavelengths in the community of Patagonia.

Over long experimental periods (i.e. days, weeks), the community composition can change toward more resistant (or highly competitive/better-adapted) species that can outcompete those that are more inhibited by the global change drivers tested, altering the magnitude of their effects. Microcosm studies conducted in Engaño bay showed that the interaction of UVR × nutrients can decrease the CO_2 sinking capacity of coastal systems by as much as 27% and that such changes are coupled with the dominance of nanoflagellates in the communities (Cabrerizo et al. 2018). These findings are crucial, as they call for the need to evaluate how the effects of solar radiation (and other global change drivers) could change over time, as Patagonia is generally considered a sink of CO_2 via the biological pump (Kahl et al. 2017). Other studies performed over long-term scales have evaluated well-known protective strategies used by phytoplankton to overcome UVR stress, such as the synthesis of specific compounds, avoidance, non-photochemical quenching, and PSII-repair rates, among others (Roy 2000). For instance, studies carried out in the Beagle channel showed that both UVR and higher temperatures promoted an increase of reactive oxygen species (ROS) as well as lipid damage (as thiobarbituric acid reactive substances, TBARS) (Hernando et al. 2018). However, these effects were partially counteracted either by the production of nonenzymatic antioxidants (α-tocopherol and β-carotene) or by the synthesis of UV-absorbing compounds such as mycosporine-like amino acids (MAAs), as also seen in a previous study (Hernando et al. 2006). Therefore, any impact determined during short-term experimentation should not be extrapolated over time as acclimation processes may significantly accentuate or ameliorate the cellular responses (Roy 2000).

Longer-term exposure to diverse scenarios of single and interacting global change drivers allowed us to determine their impact on phytoplankton nutrient (as nitrate) uptake and how it mediated the conversion into biomass along the latitudinal range of the Patagonian coast (Fig. 8). We compared studies that used the same experimental approach (in situ cluster design) and incubation time (5–7 days). This

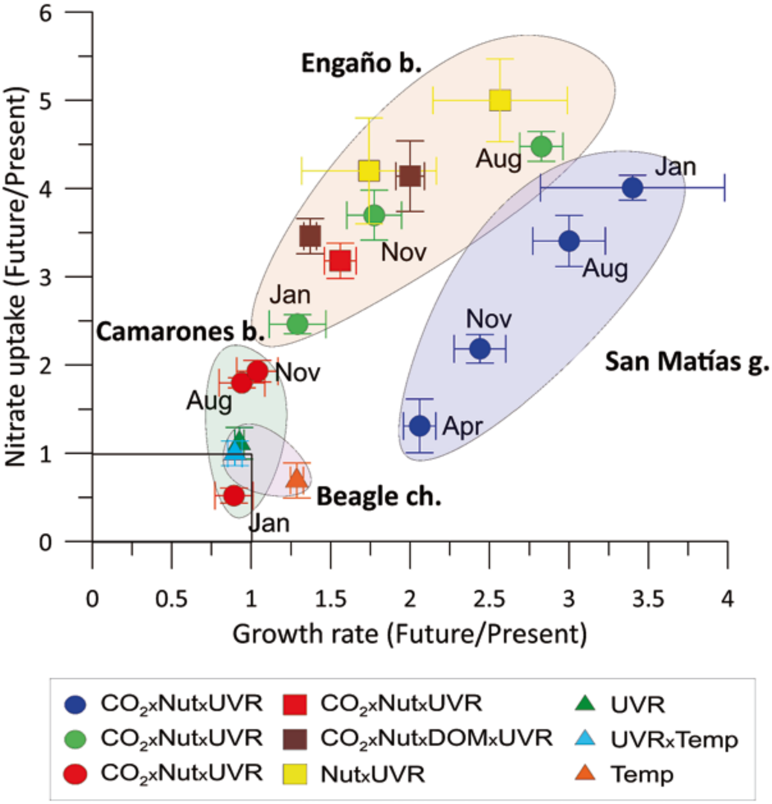

Fig. 8 Impact of future scenarios (considering various global change drivers) on growth rates and nitrate uptake of phytoplankton communities from the SWAO. Data points represent the ratio between future and present (control) scenarios in several experiments using triplicate microcosms. Error bars were calculated using error propagation. The symbols and colors indicate different studies and experiments. Data from San Matías gulf (blue dots), Engaño bay (green dots), and Camarones bay (red dots) are from Helbling et al. (unpublished). Data from Beagle channel (red, light-blue, and orange triangles) were obtained from Moreau et al. (2014); data from Engaño bay were obtained from Masuda et al. (2021) (red squares), Villafañe et al. (2018) (brown squares), and Cabrerizo et al. (2018) (yellow squares)

cluster approach had a control condition (present scenario, i.e., ambient conditions as at the time of sampling collection) and a future scenario that, depending on the study, used one to four of the following global change drivers: UVR, CO_2, Nut, DOM, or Temp. In Fig. 8, the ratio between future and present scenarios is presented for growth rates and nitrate uptake. When the ratios were 1, there were no differences between scenarios, while a ratio < 1 (or > 1) indicates lower (or higher) growth rates and/or nitrate uptake in the future scenario. The first interesting feature inferred from such results is that, regardless of the combination of variables used and the season considered, the phytoplankton communities along coastal Patagonia responded differently for each area. Second, and for most of the studies and drivers

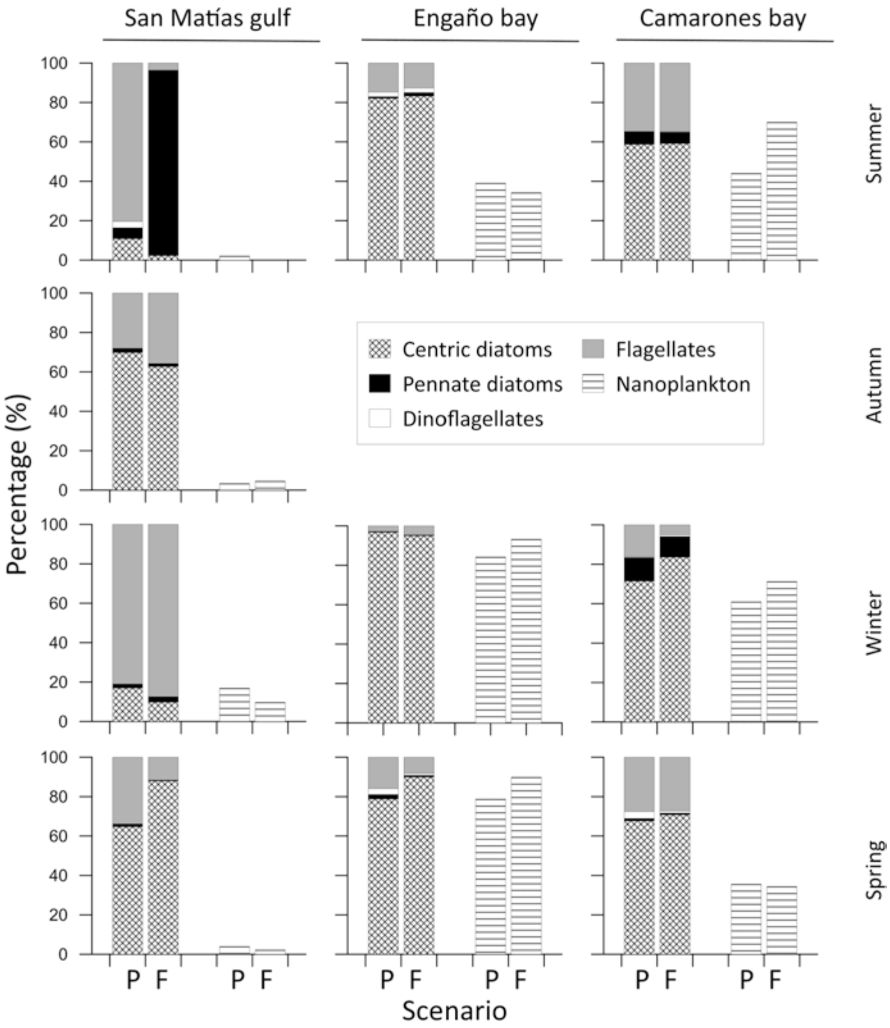

Fig. 9 Seasonal changes of phytoplankton communities exposed to future (F) and present (P) scenarios of acidification and nutrient inputs (microcosms experiments), expressed as the relative (%) carbon biomass of main phytoplanktonic groups: diatoms (centric and pennates), flagellates and dinoflagellates (stacked bars), and nanoplankton (%, single-dashed bars). Data from Helbling et al. (unpublished, as in Fig. 8)

tested, growth rates were higher in the future scenario as compared to the present (values >1), with a few exceptions; also, this impact and its variability was higher at the northern (Engaño bay, San Matías gulf) and much lower at the southern sites (Camarones bay, Beagle channel). Third, there were no clear patterns of the impact of the future scenario at different times of the year (with different water temperatures) (Fig. 8, dots with month labels). For example, at Engaño bay, the higher growth rates and nitrate uptake occurred during a bloom period (i.e., winter, August), and both parameters were much lower during the post-bloom (i.e., summer, January), while in the San Matías gulf, an increased impact "alternated" from cold to warm seasons, ending with the highest impact during summer (January). Fourth, the utilization of nutrients by each community was different, suggesting differential nutritional needs for the same growth rate. This was especially evident in Engaño bay that had higher requirements of nitrate than the other sites, most probably related to the fact that these communities are adapted to receive a riverine input of nutrients twice a day due to the semidiurnal tidal regime (Helbling et al. 2010, Bermejo et al. 2018). This was also seen in other comparative studies carried out in the Patagonia coast (Masuda et al. 2021).

In addition to changes at the metabolic level, we also evaluated taxonomic changes of natural communities occurring along a latitudinal range: San Matías gulf, Engaño bay, and Camarones bay when exposed to a future scenario of higher acidification and nutrients under different solar UVR levels along different seasons (Fig. 9). Diatoms (mostly centric) dominated both scenarios at Engaño bay and Camarones bay throughout the year, but few differences were determined between scenarios in relation to the size structure (evaluated as nanoplankton percentage). At San Matías gulf, however, significant changes were observed not only between scenarios but also among seasons. For example, pennate diatoms dominated almost completely during summer in the future scenario, while flagellates dominated in the present scenario. In autumn and spring, centric diatoms dominated, while flagellates did so in winter. In all cases, microplanktonic cells dominated at San Matías gulf. Overall, phytoplankton communities of San Matías gulf seem to be more sensitive to global change drivers, in terms of taxonomic composition and size structure, as compared with the other sites. These results evidently denote the different plasticity of species coexisting in a community and faced to global change.

Mesozooplankton

Global change impacts on mesozooplankton communities have been addressed in the context of anthropogenic influence in the form of direct input of nutrients due to urban agricultural or industrial activities. It has been suggested that, because mesozooplankton responds rapidly to changes in the environment, they can be considered valuable bioindicators of anthropogenic influence (Uriarte and Villate 2004). Thus, several studies focused on the distribution and abundance of mesozooplankton in several sites of coastal Patagonia with different degrees of human disturbance (Berasategui et al. 2018). At Puerto Pirámides, a small coastal site within the Nuevo gulf that has ship traffic due to whale-watching practices, the mesozooplankton community presented two peaks in abundance in late spring and summer (i.e., communities dominated by *Evadne nordmanni* and *Podon* spp. and the copepods *Ctenocalanus vanus*, *Paracalanus parvus*, *Calanus australis*, and *Calanoides carinatus*) and minimum abundance in winter. This general seasonal dynamic reported by Berasategui et al. (2018) did not present evident changes when comparing with previous studies (Hoffmeyer et al. 2010), suggesting a relatively low anthropogenic pressure in this site. However, the inner (with anthropogenic impact) and outer (with much less impact) zones of Ushuaia bay presented important spatial differences in the abundance and composition of the mesozooplankton assemblages: *Eurytemora americana*, *Acartia tonsa*, and the cladoceran *Podon leuckarti* characterized the inner bay, while the outer bay was represented by copepods, such as *Drepanopus forcipatus*, *Ctenocalanus citer*, and *C. brevipe*s (Biancalana et al. 2012; Berasategui et al. 2018; Presta et al. 2020). Also, *E. americana*, *P. leuckarti*, and *A. tonsa* dominated spring and summer samples of the nearby Encerrada bay (Biancalana and Torres 2011) – a site that receives high amounts of sewage effluents. These species, as well as harpacticoid copepods, were recognized as useful water quality bioindicators in samples from the Beagle channel (Biancalana and Torres 2011, 2012).

Meroplankton

Data on the effects of global change on meroplankton species in Patagonian coastal waters are also scarce, and the available evidence comes from laboratory experiments carried out with crab larvae, focusing mostly on the individual effects of artificial UVR (UV-A and UV-B) or in combination with increased temperatures. Only UV-B caused significant mortality in Zoea I larval stages of *Cyrtograpsus altimanus*, *C. angulatus*, and *Leucippa pentagona*, with *C. altimanus* being the most resistant and *L. pentagona* the most sensitive. Under higher temperatures, only *Cyrtograpsus* species showed reduced mortality, probably due to an increase in metabolic activity caused by repair mechanisms mediated by enzymes (Hernández Moresino and Helbling 2010). In *C. altimanus*, as in other metazoans, photoprotective compounds against UVR stress can be obtained indirectly from parental transferring and, also, by feeding on phytoplankton (direct acquisition) (Shick and Dunlap 2002). These compounds were found in the Zoea I stage of *C. altimanus*, and the increased bioaccumulation resulted in higher survival of larvae exposed to UVR, when comparing organisms with high and low content of these compounds (Hernández Moresino et al. 2014).

Sublethal effects of UVR, e.g., on development, body size, and motility, were also evaluated in larval stages of *C. altimanus*. Larvae that were preexposed to UVR had a delay or even an absence of molting from Zoea I to Zoea II, coupled to slower body growth, but showed enhanced swimming behavior. On the contrary, larvae preexposed only to PAR molted from Zoea I to Zoea II after 6–9 days, with a significant increase in body size, and did not change their motility (Hernández Moresino et al. 2011). Further motility studies performed with this species demonstrated the important role of UVR in conditioning the distribution of larvae in the water column, such that when UVR was absent, larvae aggregated at the surface because they swam upward. However, UVR inhibited this tendency and induced a repellent effect, which resulted in a more homogeneous vertical distribution of larvae (Gonçalves et al. 2014).

In another line of research, the effects of different pollutants were evaluated in larvae of the southern king crab (*Lithodes santolla*), an important commercial species of the Beagle channel and other parts of Tierra del Fuego and Santa Cruz provinces (Varisco et al. 2019). A sublethal concentration of the water-soluble fraction of diesel oil affected the molt success of Zoea I, and higher concentrations impaired swimming and precluded the change to the next larval stage (Amin and Comoglio 2002). Heavy metals, i.e., cadmium (Cd), lead (Pb), and zinc (Zn), were also toxic to different larval stages of this species, delaying molting and even precluding it (from Zoea II to Zoea III), such as occurred under Cd exposure (Amin et al. 2003). The exposure of eggs of *L. santolla* to Cd and Pb resulted in early hatching abnormalities (e.g., atrophy of spines and setae). Additionally, Cd also caused a significantly higher hatching rate, while Pb reduced the proportion of larvae hatching (Amin et al. 1998). Ammonia toxicity was also determined, reducing molting percentage when ammonia concentration increased, such that only Zoea exposed to the lowest concentrations could reach the post-larval stage (Diodato et al. 2019).

Concluding Remarks and Future Research

Plankton responses to global change depend on multiple factors such as the drivers, the location and timing of experimentation (which implies a particular physiological status and previous history of the community), and the cellular target or process under study. Although we have learned much about the impact of diverse global change drivers, particularly on phytoplankton, much experimental work is needed under multifarious scenarios, as the interaction among drivers tend to ameliorate their individual impacts. For example, in the coastal SWAO, the negative impacts of solar UVR on phytoplankton are generally attenuated by increased temperature, nutrients, and DOM, although within certain limits. Indeed, the predominant antagonistic effect when the number of interacting drivers increase is consistent with recent results in marine (Tekin et al. 2020) and freshwater ecosystems worldwide (Jackson et al. 2016). Multi-driver studies over the Patagonian coast have focused primarily on the combined effects of UVR and temperature/nutrients, but many important emergent combinations of global change drivers have received less attention. For instance, we are not aware of any studies evaluating how pollutants, e.g., heavy metals or microplastics, are altered by concurrent manipulations in UVR, warming, or ocean acidification. Global change abiotic drivers fluctuate in nature, but nevertheless, many studies have focused on large-scale averages across space and time using climate models; however, organisms experience and respond to local shifts that occur over hours to weeks rather than global climate change per se (Bates et al. 2018). Indeed, recent ocean-basin scale analyses show that plankton at the surface can experience thermal variations exceeding by 10 °C those predicted in a static frame (Doblin and van Sebille 2016); also, studies in upwelling systems evidence variations of 0.4 pH units in periods <24 h (Booth et al. 2012). This ecological framework is not new, as Jensen (1906) stated that the response of a particular system to average conditions is different to the response to variable conditions. Thus, Jensen's inequality ideas, together with the expected increase in environmental variability due to extreme climate events (e.g., heatwaves, storms), denote for an urgent need to re-evaluate the vulnerability of communities and ecosystems to future changes to have more realistic predictions.

Another important gap in our knowledge refers to the general lack of experimentation considering other nutritional strategies (photo- vs. mixotrophy) and trophic levels (e.g., micro- and mesozooplankton). It is essential to account for this information as, for instance, mixotrophs enhance the transfer of biomass to larger size classes and increase the sinking carbon flux, whereas herbivorous protists and animals that control phytoplankton blooms are regenerators of nutrients which fuel primary production and are sources of food for metazoans. The key role of primary consumers that can be directly affected by global change drivers, or indirectly via changes in their food, means a different equilibrium in the trophic relationships (see Valiñas et al., this volume) that also changes the CO_2 uptake and recycling within the euphotic zone. A potential higher competitive advantage (and contribution to the total community biomass) of nano- and microphytoplankton groups under future global change scenarios, as found in Patagonian ecosystems, could reduce the overall high grazing pressure (i.e., ~60% of the total primary production produced daily) found in coastal ecosystems (Calbet and Landry 2004), as larger cells seem to be comparatively less predated than smaller ones in natural communities, simply because of its size but also because they have lower nutritional quality (i.e., high C:nutrient ratios; Kiørboe 1993, Branco et al. 2020). Finally, there is an urgent need to assess the relationship between global change drivers and recurrent red tides in Patagonian coastal waters, as they can endanger marine goods and services for human beings. Thus, and overall, we have a partial understanding and views of a more complex problem than initially considered. Only with new and more integrative experimental approaches, including long time series that allow better definition of seasonal changes of diverse variables, we will be able to understand the potential impacts of global change at the ecosystem level and eventually provide solutions to mitigate it.

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Patagonian Marine Forests in a Scenario of Global and Local Stressors

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Introduction

The modification of the Earth's landscape and biodiversity by humans has been happening for thousands of years (Ellis et al. 2020), but this trend has considerably intensified since the Industrial Revolution. The impacts of such modifications are expressed in species extinctions, a changing climate, oceanographic processes,

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ecosystem deterioration, and shifts in patterns of distribution of many taxa (Díaz et al. 2019). One of the most pervasive of these changes is the increase in greenhouse gas (GHGs) emission from fossil fuel combustion, which has reverberating

Box 1: Predicting the Future: IPCC Scenarios and Ecological Change

Forecasting climate change is a complex process that needs to consider the many factors that drive global changes. One of the key variables in such predictions is the amount of GHGs present in the atmosphere. These gases trap heat radiating from the Earth's surface back to space, and the amount of gases in the atmosphere is directly related to how much heat is kept (Hartmann 2016). Accordingly, the climate models developed by the use of different scenarios of GHG emissions, among other important variables such as land use, atmospheric concentrations, and air pollutant emissions, to project the future climate (IPCC 2014). These scenarios are called the Representative Concentration Pathways (RCPs), the four different pathways for the twenty-first century. Each scenario represents different efforts to reduce emissions: RCP 2.6 is the stringent mitigation scenario, in which the increase in the average global temperature stays likely below 2 °C above pre-industrial temperatures; RCP 4.5 and RCP 6.0, which represent different levels of intermediate mitigation; and RCP 8.5, a scenario where there are no additional efforts to constrain emissions (IPCC 2014).

These scenarios feed atmosphere-ocean general circulation models and, therefore, make it possible to predict the degree of increase in ocean temperature, sea level, extreme events, salinity, and so forth, according to the route of mitigation simulated (IPCC 2019). Recently, scientists made a united effort to create data layers for present and future environmental ocean conditions, such as the Bio-ORACLE database, based on these general circulation models and pathways of emissions (Tyberghein et al. 2012; Assis et al. 2018). The availability of such data layers allows researchers to explore and describe the global distribution of species in different time periods and predict how global changes will affect marine species (Torossian et al. 2016). One of the tools used to determine the relationship between the environment and species distributions are Ecological Niche Models (ENMS). ENMs correlate occurrences of the species in the geographical space with the values of environmental variables in each of these occurrences to estimate the niche of the species (Peterson et al. 2012). Then, the model is projected to the geographical space where it finds regions with similar environmental conditions to the occurrences of the species (Wiens et al. 2009). Consequently, it is possible to generate a map of habitat suitability[1] that identifies areas (in the present and in the future) that can possibly be inhabited by the species, based on the environmental conditions of known occurrences (Elith and Leathwick 2009). Therefore, databases such as can be used to determine the potential current and future distribution of marine species.

[1] Habitat refers to the environmental conditions that a species needs to grow and maintain viable populations (Guisan et al. 2017).

impacts in global climate and biogeochemical systems (Box 1). However, human settlement and economic practices bring many other impacts and modifications to the biosphere. The need to sustain the ever-increasing human population is reflected in food and energy production, industry, and urbanization, each with their own and combined impacts (Steffen et al. 2004).

In marine ecosystems, the combination of these stressors results in a highly complex scenario associated with the observed global loss of marine biodiversity. Recent evidence supports the fact that the warming process in the ocean, from surface to bottom, is unmistakable (Johnson and Lyman 2020; Meinen et al. 2020). Ocean warming already induces species to seek refuge or favorable environmental conditions within their fundamental niches, and changes in the distributional range of species are expected to become more frequent in the future (Pecl et al. 2017). A migratory flow toward the poles is expected, with a consequent "tropicalization" of the temperate ecosystems (Vergés et al. 2014; Inagaki et al. 2020). The arrival of new species will lead to the establishment of new interactions and the modification or loss of old ecological and coevolutionary relationships (Blois et al. 2013).

The impacts of the arrival of new species to local assemblages are already seen in marine bioinvasions. Invasive species have transformed marine communities around the world, driving serious ecological and economic impacts (Molnar et al. 2008). Although the impacts of bioinvasions are local, they are usually the consequence of global factors, such as increasing international trade and ship traffic (Hulme 2009; Early et al. 2016). The invasion process is also facilitated when the native community is already disturbed by either local stressors, such as eutrophic coasts and the expansion of aquaculture, or global changes (Shea and Chesson 2002). Therefore, global change not only promotes alterations of marine ecosystems by increasing levels of extinctions and displacement of species distributions, but it also introduces new species in local assemblages, ultimately driving the establishment of new communities. In order to understand the future of Patagonia's marine flora, it is first necessary to assess the environmental changes happening in the region at the moment and then look at how the future trends of these changes will affect the biodiversity of this important region.

Environmental Changes and the Patagonian Marine Flora

Many of the stressors observed globally have also been recorded along the South American coast, and their impacts on Patagonian marine forests are expected to increase in the near future. In this context, a consistent increase in air temperature and in the frequency of heatwaves has been recorded throughout the twentieth century in Argentina, apparently affecting the Patagonian region more strongly (Rusticucci and Barrucand 2004; Barros et al. 2015). At the same time, coastal and oceanic water masses also became warmer in the region (see Saraceno et al., this volume), resulting in changes in the distribution of the marine biota poleward, especially fauna (Johnson and Doney 2006; Bovcon et al. 2011; Franco et al. 2020).

In the past half century, there was also a consistent increase in the concentration of carbon dioxide (CO_2) in water masses of the Argentine basin (Fontela et al. 2021). Such an elevation in CO_2 content raises concern about the levels of ocean acidification along the eastern Patagonia. Despite the lack of data on nearshore habitats, ocean acidification is expected to severely impact the entire Southern ocean in the next decades (Figuerola et al. 2021), affecting many highly sensible species that also inhabit the Patagonian coast (see Narvarte et al., this volume). This acidification scenario, however, is complex since sea-air fluxes of CO_2 change along the Patagonian shelf, with nearshore regions acting as a source of CO_2 to the atmosphere (see Villafañe et al., this volume), whereas mid-shelf areas act as a sink (Bianchi et al. 2005). Additionally, coastal waters off the Argentinian Patagonia have naturally large seasonal variations in the state of $CaCO_3$ saturation (Steinacher et al. 2009), meaning that the risk of calcium carbonate dissolution may vary along the year (Figuerola et al. 2021).

Such spatial and temporal variations in factors related to ocean acidification are usually associated with changes in phytoplankton primary production throughout the Patagonian shelf (Bianchi et al. 2005; Steinacher et al. 2009). It is unclear, however, how such a stressor will affect the marine forests in the region. It is usually considered that an increased CO_2 concentration can benefit at least some macroalgae (van der Loos et al. 2019). Also, experimental studies in controlled environments with the most abundant kelp species of Patagonia (i.e., *Macrocystis pyrifera* and *Undaria pinnatifida*) indicated that neither ocean acidification alone nor combined with ocean warming result in significant damage to the development, growth, or photosynthesis of these seaweeds (Fernández et al. 2015; Leal et al. 2017a, b). However, the concomitant occurrence of other factors (such as pollutants) may trigger or exacerbate eventual negative effects on these same kelps (Leal et al. 2018). Furthermore, the influence of ocean acidification and warming on other components of the ecosystems (such as primary consumers and other primary producers) cannot be ruled out (Figuerola et al. 2021). Thus, new field studies are needed to clarify the interactive effects of ocean warming and acidification on Patagonian marine forests.

Regarding other biotic stressors, even though the Southwest Atlantic ocean is relatively isolated from the main routes of marine transport, it has not escaped from the phenomenon of species invasions (Orensanz et al. 2002; Schwindt et al. 2014). On the contrary, this is currently one of the most prevalent risks to Patagonian marine forests. In some places, for example, a quarter of all macroalgae species are introduced or cryptogenic, and the structure of such phytobenthic communities has been substantially altered (Raffo et al. 2014). A particularly worrisome case is the introduction of *Undaria pinnatifida* (Harvey) Suringar, which was recorded in Argentina for the first time in December 1992, and since then it has exhibited strong invasive and competitive behavior (Casas et al. 2004). The impacts of *U. pinnatifida* on marine ecosystems are complex, with ecological, economic, and hydrological consequences (Bunicontro et al. 2019). Due to the size of the species and its potential to reach high biomasses, *U. pinnatifida* may alter the seascapes. The species can outcompete native seaweed species (Casas et al. 2004, but see Raffo et al. 2009) and affect the trophic structure of the ecosystems, sometimes even increasing the richness and abundance of consumers (Irigoyen et al. 2011b). It may also harm the stocks of economically important species (Casas et al. 2004). In this regard, the arrival, in some localities, of huge masses of stranded mats have been discouraging tourism and caused the degradation of coastal zones, resulting in important economic losses (Bunicontro et al. 2019).

In addition to macroalgae, the introduction of animal species has also been causing substantial impacts on Patagonian marine forests. For example, the solitary ascidian *Styela clava* Herdman was introduced almost simultaneously with *U. pinnatifida* in northern Patagonia (Pereyra et al. 2015). Both species interact, and it has been shown that the former may facilitate the settlement and growth of the latter by increasing substrate complexity (Pereyra et al. 2015, 2017). Another remarkable case is the introduction of the Pacific oyster *Magallana gigas* (Thunberg 1793), which now form extensive “beds” on stretches of rocky shores, altering the structure of intertidal ecosystems (Croce and Parodi 2012). Such beds may actually increase substrate complexity, potentially resulting in higher species richness and abundance of organisms at higher trophic levels (Escapa et al. 2004). Nevertheless, the flora associated with these habitats is usually distinct, often dominated by few red algae species, which suggests substantial alterations to the structure of the phytobenthos (Croce and Parodi 2012).

Lastly, increases in nutrient inputs, usually associated with increased urbanization, are yet another source of stress to Patagonian marine forests. Eutrophication and pollution in coastal environments have been reported along the Argentine coast, resulting in the contamination of the marine biota (Marcovecchio et al. 1994; Gil et al. 2019) and with important changes in seaweed biomass and species composition. For example, opportunistic Chlorophyta species (such as *Ulva* spp.) seem to thrive in such conditions and have been altering the structure of the Patagonian phytobenthos (Diaz et al. 2002; Piriz et al. 2003; Martinetto et al. 2010). It is noteworthy that changes in the hydrological regime are among the most common impacts reported due to climate change in Patagonia. In particular, an increase in precipitation is projected in the northern regions, but a decrease in rainfall is expected in the south (Barros et al. 2015; Pessacg et al., this volume). These changes will affect the freshwater inputs to coastal ecosystems (Aguayo et al. 2019), altering the nutrient budget in the continent-ocean interface. However, it is still not clear how these hydrological modifications will influence the continental runoff and discharge of pollutants into coastal areas, nor how such an expected decrease in continental subsidies will affect the Patagonian marine forests.

It must be stressed that long-term environmental changes act synergistically with seasonal variations and extreme events. There is also a considerable interaction among abiotic (i.e., ocean warming and acidification, reduced precipitation, and decreased continental subsidies to coastal ecosystems), biotic (invasive species), and anthropogenic (pollution) stressors. These interconnections result in a multifaceted and complex picture. New studies are thus urgently needed to evaluate the joint impacts of these numerous environmental stressors on Patagonia’s marine forests. In this context, the present chapter aims to identify major trends of environmental change affecting the marine flora of Patagonia. We first propose a biogeographical regionalization of this phycoflora, in order to highlight the baseline and identify the main abiotic drivers affecting the large-scale distribution of species and to discuss how future scenarios can alter the composition of seaweed assemblages. Then, we focus on two representative species, the native kelp *M. pyrifera* and the invasive kelp *U. pinnatifida*, whose current and future distributions were modeled considering different projected IPCC scenarios, highlighting important factors of global and local environmental change.

Biogeographical Regionalization of Patagonia's Marine Flora

There is a clear latitudinal gradient in seaweed diversity along both Atlantic (Liuzzi et al. 2011) and Pacific (Santelices and Marquet 1998) coasts of Patagonia. In both oceans, the number of species increases from north to south, and the southernmost tip of South America has one of the highest macroalgae richness of the continent, with about 150 species (Fig. 1). Such an inverse latitudinal diversity gradient (i.e., the number of algae species increases from the equator to the poles, unlike most marine and terrestrial taxa) is commonly reported for macroalgae but so far remains unexplained (Kerswell 2006; Kindlmann et al. 2007).

Besides species diversity, species composition also changes from north to south along the eastern and western coasts of South America. Such a pattern has been well

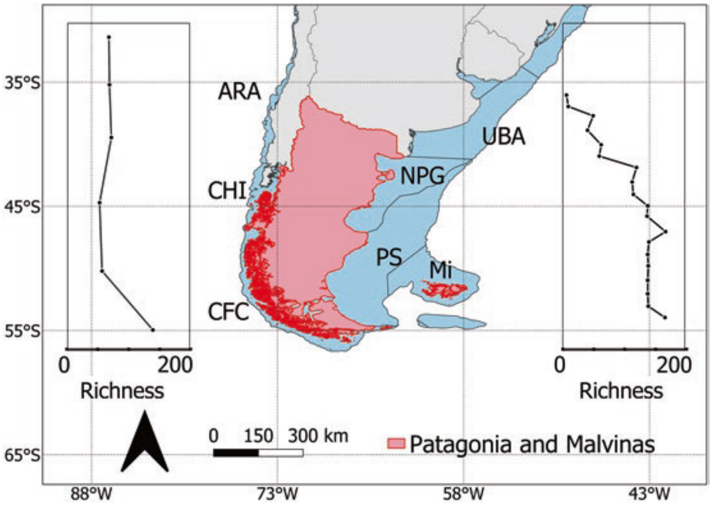


Fig. 1 The map of Patagonia illustrating the latitudinal gradient in seaweed species richness. Both the Atlantic (latitudinal gradient based on Liuzzi et al. 2011) and Pacific (gradient based on Santelices and Marquet 1998) coasts are shown. The acronyms represent marine ecoregions of the temperate South America realm according to Spalding et al. (2007): *UBA* Uruguay-Buenos Aires shelf, *NPG* north Patagonian gulfs, *PS* Patagonian shelf, *Mi* Malvinas islands, *CFC* channels and fjords of Southern Chile, *CHI* Chiloense, *ARA* Araucanian

documented for the Pacific Patagonia (Santelices 1980; Meneses and Santelices 2000; Santelices and Meneses 2000); however, the seaweed biogeography along the Atlantic coast is less well established.

From a biogeographical point of view, Spalding et al. (2007) included the whole Patagonia region in the Magellanic province of the Temperate South America marine realm. The authors further divided the Magellanic province into five ecoregions, from east to west: the north Patagonian gulfs (NPG), Patagonian shelf (PS), Malvinas (Mi), channels and fjords of Southern Chile (CFC), and Chiloense (CHI). This same regionalization scheme can be largely applied for Patagonian seaweeds. In the present study, we compiled macroalgae species occurrence data from Coll and Oliveira (1999), Ramirez (2010), Liuzzi et al. (2011), Menezes et al. (2015), and Oliveira et al. (2020), encompassing the coasts of Antarctica, Chile, Argentina, Uruguay, and Brazil. An analysis of these data indicate that the Patagonian marine flora can be divided into a northeastern component (corresponding to the NPG), a southeastern component (PS), and an island component (Mi and CFC, which are likely distinct, being grouped together due to the lack of data in the analysis). Moreover, these components are remarkably distinct from the colder flora of Antarctica and the warmer (or freshwater) flora observed north of Argentina and above (including the Uruguay-Buenos Aires shelf ecoregion and the warm temperate Southwestern Atlantic and tropical Southwestern Atlantic marine provinces), confirming the distinctness of the Patagonian phycoflora (Fig. 2).

Regarding the differences among the three Patagonian flora, an analysis of the Pearson's *phi* coefficient of association (Chytrý et al. 2002) suggested a high fidelity of many invasive species (classified as such according to Raffo et al. 2014) to the NPG, such as *Anotrichium furcellatum* (phi = 1, p = 0.005), *Cutleria multifida*, *Dictyota dichotoma*, *Neosiphonia harveyi*, *Polysiphonia brodiei*, *U. pinnatifida* (all with phi = 0.91, p = 0.005), and *Porphyra linearis* (phi = 0.71, p = 0.015). But even after removing these alien species, the biogeographical differences among Patagonian regions remain, and species such as *Codium vermilara* (phi = 0.91, p = 0.005) and *Streblocladia corymbifera* (phi = 0.71, p = 0.015), which are among the most abundant on shallow subtidal habitats (Casas et al. 2004), have a high fidelity with the NPG.

Compared to the NPG, both the PS, MF, and CFC have a higher fidelity of some cold-adapted species, which may also be found in Antarctica. The PS, for example, is related to the occurrence of the coarsely branched *Cladodonta lyallii*, the filamentous *Cladothele striarioides*, the endophyte *Colaconema daviesii*, the crustose *Hildenbrandia lecannellieri*, and the kelp *Lessonia fuscescens* (all with phi = 1, p = 0.005). Both regions, however, have distinct floras; neither has typical Antarctic marine vegetation; and the CFC is also known to have a species composition different from that of the central and northern Chile (Santelices and Meneses 2000). Additionally, many seaweed species are found in all Patagonian ecoregions, notably the kelps *M. pyrifera* and *Lessonia vadosa*. The joint occurrence of these (and other) species help to characterize the unique Patagonian phycoflora.

To investigate how environmental factors may have influenced the differentiation of Patagonian phytogeographic regions, we performed a distance-based redundancy

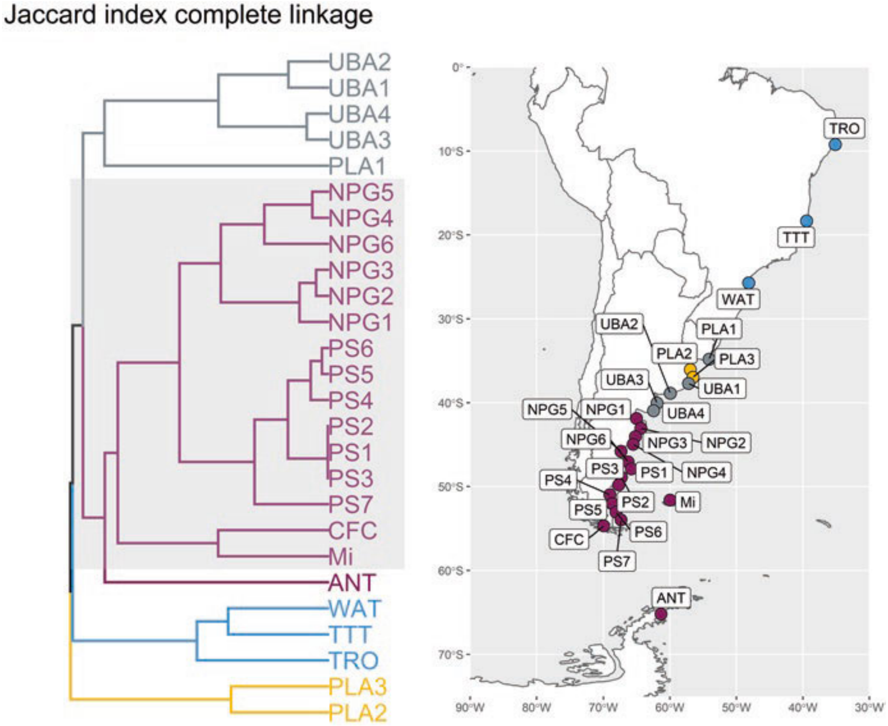
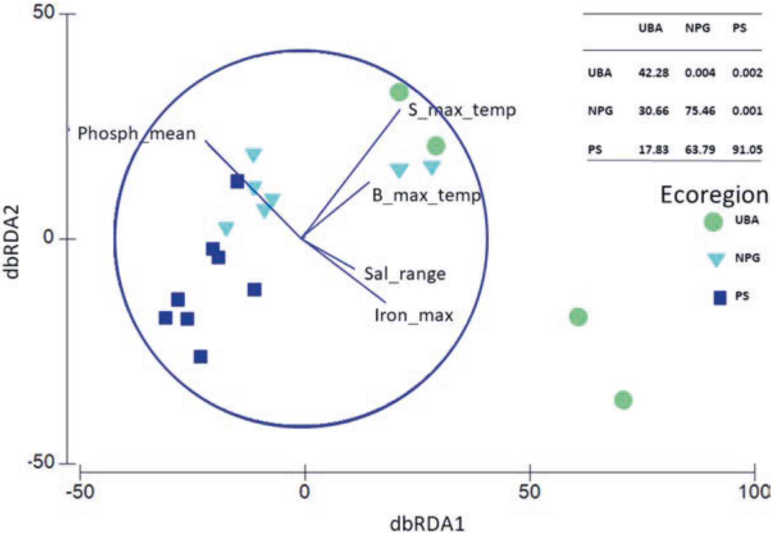


Fig. 2 A dendrogram of 26 locations along the temperate South America, Southern ocean, and Tropical Atlantic marine realms (*sensu* Spalding et al. 2007) illustrating the uniqueness of the Patagonian seaweed flora (locations within the shaded rectangle). A dendrogram constructed by complete-linkage hierarchical clustering using the Jaccard index, which was calculated from occurrence data (i.e., presence/absence) of 1306 macroalgae species. The map on the right indicates the sites for the analysis. The acronyms are as follows: *UBA* Uruguay-Buenos Aires shelf, *NPG* north Patagonian gulfs, *PS* Patagonian shelf, *Mi* Malvinas islands, *CFC* Tierra del Fuego, *ANT* Antarctica, *WAT* warm temperate Atlantic, *TTT* Atlantic tropical-temperate transition, *TRO* tropical Atlantic; and PLA, Río de la Plata

analysis (dbRDA) (Legendre and Anderson 1999). This analysis was performed in PRIMER-E software version 6.1.18 (Anderson 2005), considering only sites along the Argentinean coast (PS, NPG, and the northern Uruguay-Buenos Aires shelf) which have a relatively large number of samples considering the latitudinal gradient, using the species list compiled by Liuzzi et al. (2011). The environmental factors used to constrain the ordination were retrieved from the Bio-ORACLE database (Assis et al. 2018), considering nearshore coordinates (0–15 m deep) at the same latitudes as indicated by Liuzzi et al. (2011) (i.e., from 36°S to 55°S), and selected using the PERMANOVA-DISTLM Primer 6.0 routine. The dbRDA (Fig. 3) resulted in an ordination of sites with similarities significantly influenced by factors related with the three ecoregions, and the two first axes explained 60.4% and 22.7% of the total observed variability, respectively; the observed lower intra-similarity of the northern ecoregions reinforces the transition between the temperate and the warmer



	UBA	NPG	PS
UBA	42.28	0.004	0.002
NPG	30.66	75.46	0.001
PS	17.83	63.79	91.05

Fig. 3 Results of the distance-based multivariate multiple regression (DistLM) of Patagonia flora data overlaid with the partial correlations of the significant environmental variables identified by the best models using the AICc criterion. The redundancy analysis (dbRDA) grouped the occurrences by ecoregions, represented by different symbols and colors. Data dispersion is explained by physical factors, related to temperature, salinity, and nutrient concentration, explaining 60.4% (axis dbRDA1) and 22.7% (axis dbRDA2) of the total variation considering the two first axes, respectively. The table on the right presents the PERMANOVA results, with intra-similarity of each ecoregion in bold at the diagonal, with the p values of differences between ecoregions above, and the respective similarities between them appear below. (Sorensen's similarity index)

province (Spalding et al. 2007). The PERMANOVA also highlights the lower similarity observed between the extremes of Magellanic province, reinforcing the physical and chemical particularities of each ecoregion observed along this latitudinal gradient (Garaffo et al. 2020). The analysis indicated that the geographic differences in species composition can be related to changes in temperature and freshwater inputs (represented by a higher phosphate concentration in marine waters) along the Patagonian coastline (Fig. 3). Northern sites are usually warmer and have a higher mean precipitation than southern locations, a gradient that has a marked effect on the distribution of the biota (Paruelo et al. 1998). Additionally, the high concentration of iron on the coast of some southern sites (also depicted in Fig. 3) seems to be more related to aeolian and erosive inputs, than to riverine loads (Gaiero et al. 2003).

The biogeographic regionalization of the Patagonian marine flora and the dbRDA results indicate possible trends for the impacts of environmental changes on macroalgae communities of temperate South America. The expected climate warming may exclude cold-adapted species from the southern portions of Patagonia, namely, the Patagonian shelf, the Malvinas, and the channels and fjords of Chile ecoregions (*sensu* Spalding et al. 2007). This area is a continental hotspot of seaweed biodiversity, and such a loss of species, if it really happens, may have dramatic consequences to the functioning of ecosystems. Additionally, a tropicalization of these areas may favor a southward spread of invasive species, which apparently are still affecting the north Patagonia gulf ecoregion more strongly. Such spread may act synergistically with climate warming, further increasing the risk of biodiversity loss at the tip of South America. Additionally, we have detected an important influence of freshwater inputs on the marine phytogeography of Patagonia. As mentioned previously, a decrease in rainfall (and consequently of freshwater inputs) is expected in the south of the region, while the north may face increased precipitation. It is unclear, however, if and how these changes will affect seaweed communities. New studies are needed to assess spatial and temporal patterns of coastal water physicochemical parameters in order to generate future scenarios considering precipitation and runoff changes. Despite the importance of the latitudinal gradient to influence species distribution, the presence of intertidal sewage effluents drives diversity patterns and can mask the effects of macroecological scenarios (Garaffo et al. 2020). These studies will be even more valuable if they include a discussion on the risks and impacts of ocean acidification.

Among these stressors, the spread of alien species seems to be a more prominent threat to the Patagonian marine forests, since it has already been documented as an important source of negative impacts (Casas et al. 2004; Raffo et al. 2014; Bunicontro et al. 2019). Therefore, in the next section of this chapter, we investigate current and future distribution patterns of key seaweed species, namely, the kelps *M. pyrifera* and *U. pinnatifida*.

Current and Future Distribution of Patagonian Kelp Forests

From an ecological perspective, the Patagonian marine flora appears in different physiognomies, with K and r strategist species, and perennial (Raffo et al. 2014), opportunistic (Torres et al. 2004) and ephemeral populations (Karez et al. 2004) composing intertidal and subtidal habitats (Fig. 4). Among these different macroalgae assemblages, kelp forests stand out. These habitats are formed by large (reaching up to tens of meters) brown algae species such as *M. pyrifera* and *Lessonia* spp., which are considered ecosystem engineers of enormous ecological importance. Due to their height and canopy-forming habit, these kelps form true marine forests (*sensu* Wernberg and Filbee-Dexter 2019), providing refuge and substratum for a significant variety of marine organisms (Moreno and Jara 1984). Also, it is known that kelp plays an important role and ecosystem service in nutrient cycling, especially in the uptake, storage, and transfer of carbon, in coastal marine ecosystems (Mann 1972; Salomon et al. 2008).

The morphology of kelps reflects an interchange between maximizing nutrient and light absorption while minimizing drag- and wave-induced dislodgement and mortality (Fig. 5). In particular, many kelp species have invested in morphological adaptations to wave exposure such as larger and stronger holdfasts, shorter and

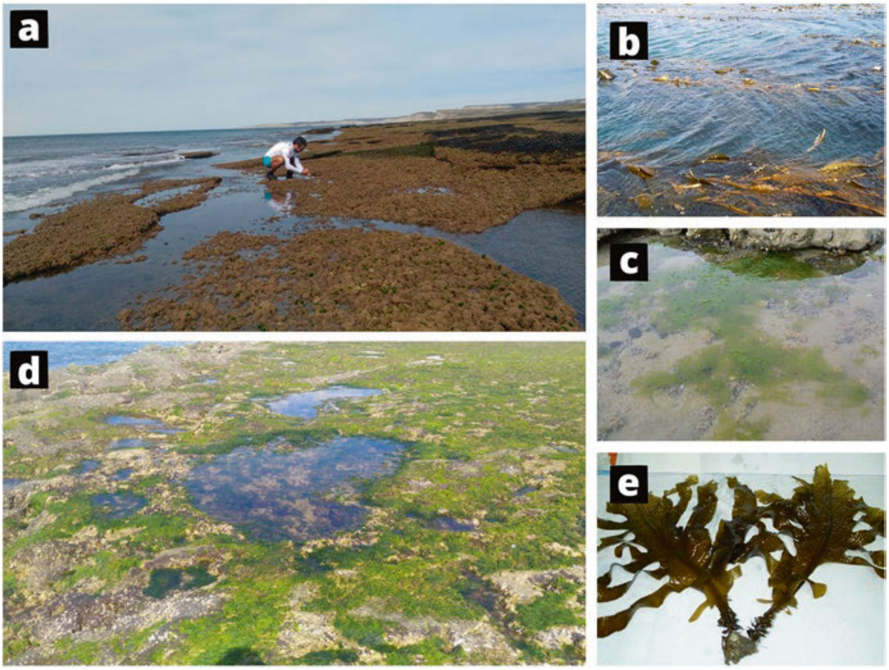


Fig. 4 Different physiognomies from the intertidal perspective (**a**–**d**) of macroalgal-dominated environments in Patagonia. (**a**) Intertidal rock reef dominated by the perennial beds of *Corallina officinalis*. (**b**) The perennial *Macrocystis pyrifera* kelp forest with the distal portion observed floating on the surface. (**c**) Rock pool dominated by the opportunistic and r strategist *Ulva* sp. (**d**) Intertidal rock reef dominated by *Ulva* sp. (**e**) Exsicata of *Undaria pinnatifida*. (**a**–**d**): photos by E. W. Helbling. (**e**) photo by F. Figueroa

Fig. 5 Subtidal perspective of macroalgal-dominated habitat with canopy structured by *M. pyrifera* kelp in Malaspina inlet (Bustamante bay, Chubut, Argentina). **1**: Photo by _Kartenn, licensed under CC BY-NC-ND 2.0. **2** and **3**: Photos by M. Marcinkevicius

thicker stipes, and more streamline blades that reduce drag (Gaylord and Denny 1997; Wernberg and Thomsen 2005). Also the occurrence of kelp-dense forests is related to the combination of high availability of light (Sjøtun et al. 1998; Bartsch et al. 2008), cool temperatures (Smale et al. 2019), and wave exposure (Sjøtun et al. 1998; Gorman et al. 2013).

To assess the current and future ranges of Patagonian kelp forests, we constructed distribution models for two of the most common kelp species in the region: the native *M. pyrifera* and the invasive *U. pinnatifida*. To build these models, occurrence data for both species were retrieved from the Global Biodiversity Information Facility (GBIF 2021a, b). These data were inspected for duplicate or clearly wrong entries (such as occurrences outside the ocean), and to reduce spatial sampling bias (Phillips et al. 2009), we thinned occurrences within a 10-km radius using the R package "spThin" (Aiello-Lammens et al. 2015). For *M. pyrifera*, we used data from Argentina, Uruguay, Chile, and Antarctica, resulting in 64 occurrences. As for *U. pinnatifida*, data from the entire world were used, as models for invasive species tend to yield better and more accurate predictions when the native and invasive range of occurrences are used (Broennimann and Guisan 2008). After filtering as mentioned before, 188 *U. pinnatifida* occurrence points were considered.

To explain and predict the occurrence patterns for both kelp species, we used bottom-of-the-ocean environmental data from the Bio-ORACLE database (Tyberghein et al. 2012). The environmental variables included in the models were selected according to their biological significance and low multicollinearity (i.e., variance inflation factor < 10) (Table 1) (Chatterjee and Hadi 2006; Naimi et al. 2014). To predict the future distribution of both species, the chosen environmental variables represented both present-day conditions and future projections (year 2100) considering two greenhouse gas emission scenarios: (1) a scenario assuming a strong mitigation of current fossil fuel emissions (RCP 2.6) and (2) a scenario where emissions stay business-as-usual (RCP 8.5) (see Box 1). In implementing the model, variable importance was calculated through a randomization process using Pearson's correlation with three iterations (for further explanation on the process, see Thuiller et al. 2019). Response curves to maximum temperature were also generated based on the evaluation strip method (Elith et al. 2005), which shows the sensibility of the model to variations in maximum temperature when all the other predictors are set to a fixed value (here, the mean) (Table 1).

Ensemble species distribution models were built with kelp occurrence and environmental data using the "biomod2" R package (Thuiller et al. 2019), using five

Table 1 Environmental predictors used in both models

Macrocystis pyrifera model	*Undaria pinnatifida* model
Maximum temperature (°C)	Maximum temperature (°C)
Minimum phosphate (μmol L^{-1})	Minimum dissolved oxygen (μmol m^{-3})
Minimum dissolved oxygen (μmol m^{-3})	Minimum depth (m)
Minimum current velocity (m s^{-1})	Maximum salinity
Maximum salinity	Minimum nitrate (μmol L^{-1})

individual runs of three machine learning algorithms (gradient boosting machines (GBM), artificial neural networks (ANN), and random forests (RF)). As these models require presence/absence data, 5 sets of 64 pseudo-absences for *M. pyrifera* and 188 for *U. pinnatifida* were generated 2° apart from the occurrences points, according to the recommendations of Barbet-Massin et al. (2012). To allow model evaluation, in each run, the data was split between a calibration and a validation set (70%/30%, respectively). Model performance was determined by two evaluation metrics: the area under the receiver Operating characteristic curve (AUROC) (Fielding and Bell 1997) and the true skill statistics (TSS) (Allouche et al. 2006). AUROC varies from 0.5 (models with no predictive ability) to 1 (models with perfect predictions) (Pearson et al. 2006); TSS ranges from -1 to 1, where values equal or lower to 0 indicate model performance no better than random and +1 indicates perfect prediction (Allouche et al. 2006). The final ensemble models were built only with models that obtained TSS above 0.8. The ensemble algorithm used was committee averaging (the average of binary predictions), and the coefficient of variation of probabilities was also run to measure the uncertainty of predictions (Thuiller et al. 2019).

The final ensemble models produced accurate estimates of the present-day occurrence of both *M. pyrifera* (TSS = 0.934 and AUROC = 0.997) and *U. pinnatifida* (TSS = 0.947 and AUROC = 0.998). The binary prediction of current habitat suitability for *M. pyrifera* showed that suitability for this species starts in the coast of Uruguay, but it is more spatially significant in the Patagonia region, Malvinas islands, and Chile (Fig. 6A). Meanwhile, *U. pinnatifida* habitat suitability begins on the Brazilian coast and extends until San Jorge gulf, in Patagonia (Fig. 6B). The most important variable to describe the distribution of *M. pyrifera* was maximum

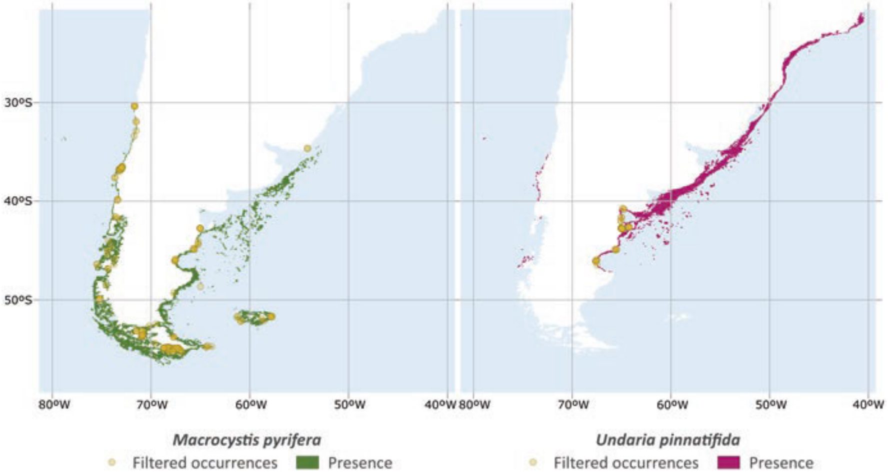


Fig. 6 Binary map of (**A**) *M. pyrifera* and (**B**) *U. pinnatifida* habitat suitability under current environmental conditions. Filtered presences from GBIF used in models are presented in yellow circles

temperature, followed by minimum phosphate, minimum dissolved oxygen, minimum current velocity, and maximum salinity (Fig. 7A). As for *U. pinnatifida*, the most important variable was also the maximum temperature, followed by minimum dissolved oxygen, minimum depth, maximum salinity, and minimum nitrate (Fig. 7B).

The final models also indicate that projected future climate change scenarios will have substantial impacts on the distribution of Patagonian kelp forests. Projections of habitat suitability in future environmental conditions (Fig. 8) showed a shift in the distribution of both species in either decreasing or increasing GHG emission scenarios (i.e., RCP 2.6 and RCP 8.5, respectively), but these shifts are more pronounced in RCP 8.5. Under RCP 2.6, the predicted loss of suitable habitats is 5.5%/2.7% (*M. pyrifera*/*U. pinnatifida*), while the gain is 9.8%/20.2% (Fig. 8A, C). Under RCP 8.5 (Fig. 8B, D), there is a bigger loss of suitable habitats (24.5%/8.4%), but the gain is also bigger (15.5%/80.4%). The spatial overlap of habitat suitability of the two species shows that in current environmental conditions, 8.9% of *M. pyrifera* habitat suitability is shared with *U. pinnatifida*, a percentage that is predicted to increase in both emission scenarios, to 11.4% in RCP 2.6 and to 15.5% in RCP 8.5 (Fig. 9).

Our model of *U. pinnatifida* showed habitat suitability for this species throughout a significant portion of South America's coast, but its overlap with *M. pyrifera* in Patagonia is restricted by temperature. While *M. pyrifera* has a higher probability of occurrence in regions with maximum temperatures between ca 7 °C and 20 °C, *U. pinnatifida* has higher affinity with maximum temperatures > 15 °C (Fig. 10). As such, this restricts the current presence of *U. pinnatifida* in southern Argentina and Chile, as well as in Malvinas islands, where much of *M. pyrifera* potential distribution is found.

These results are in accordance with the thermal limits reported in the literature for both species. *M. pyrifera* has been reported to be found in temperatures between 12 and 20 °C (Macaya et al. 2005), and in experimental assessments, individuals

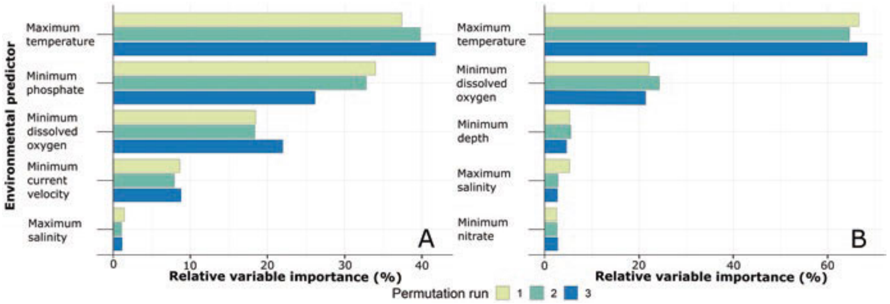


Fig. 7 Relative importance of variables used in (**A**) *M. pyrifera* and (**B**) *U. pinnatifida* models, represented in percentage. Each bar represents one iteration run. The higher the value, the more influence the variable has on the model

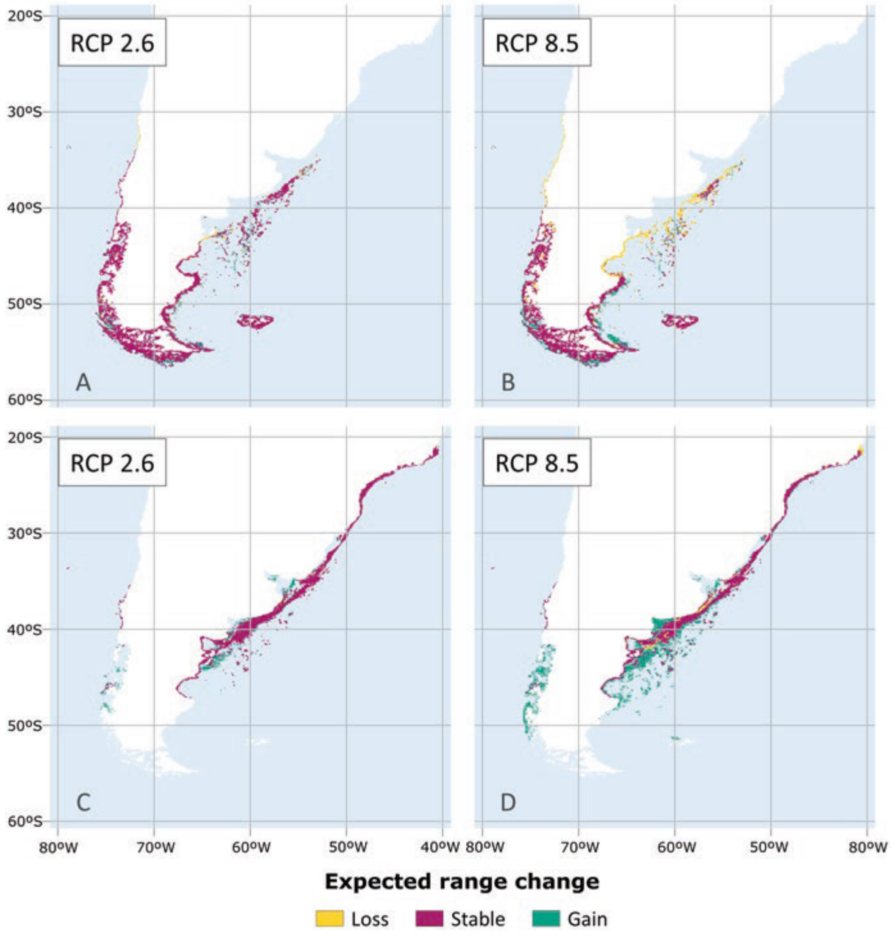


Fig. 8 Future projections (2100) of (**A–B**) *M. pyrifera* and (**C–D**) *U. pinnatifida* under the scenarios of RCP 2.6 and 8.5, respectively

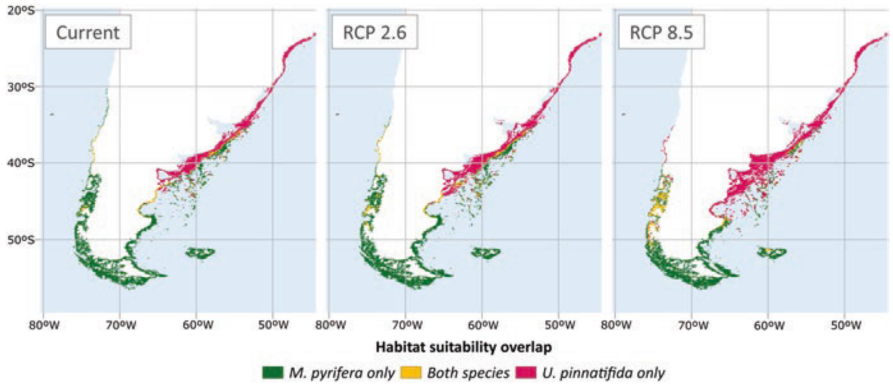


Fig. 9 Maps of habitat suitability overlap between *M. pyrifera* and *U. pinnatifida*, under current and future (2100, RCP 2.6 and 8.5 environmental conditions, respectively)

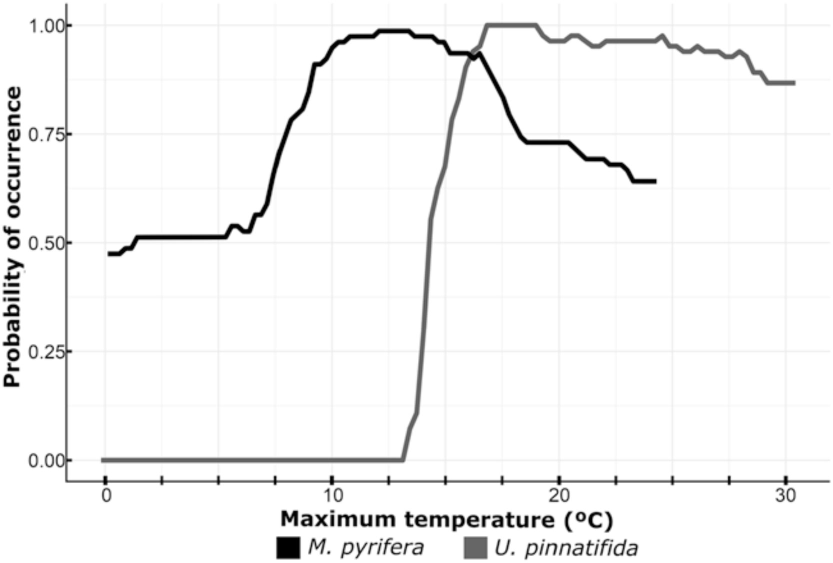


Fig. 10 Response curve of *M. pyrifera* and *U. pinnatifida* to variations in maximum temperature. The curve shows the probability of occurrence of the species in the range of temperature

demonstrated certain tolerance to elevated temperatures (Fernández et al. 2021; Hollarsmith et al. 2020). As for *U. pinnatifida*, although its adult invasive sporophytes in experimental evaluations had reduced photosynthetic rates in elevated temperatures, these higher temperatures do not reduce its survival or photosynthetic efficiency (Bollen et al. 2016). Therefore, there is a reduction in the fitness of the species, but it still allows the presence of the species in regions with warmer temperatures. However, the relative growth rate of *U. pinnatifida*'s juvenile sporophytes is greater at 15 and 20 °C, but it seems not to support temperatures higher than 24 °C (Gao et al. 2013). Also, experiments revealed that gametophytes of *U. pinnatifida* cannot survive temperatures > 28 °C, and in that case, the growth rate is inhibited (Watanabe et al. 2014). These studies indicate that there is a difference in physiological tolerances in different life stages and between native and invasive populations of *U. pinnatifida*, very likely resulting in distinct invasive potentials between populations and life stages. Our model does not capture these differences, and further studies investigating the impacts of local adaptation and ontogeny on the distribution of *U. pinnatifida* are necessary to make more accurate predictions of its invasive potential in both current and future environmental conditions.

Our projections to 2100 in both emission scenarios show the expansion of *U. pinnatifida* habitat suitability to currently colder-water regions, following the tropicalization trend. At the same time, *M. pyrifera* loses habitat suitability in these regions, especially in RCP 8.5 where it is lost down to the San Jorge gulf, and its potential distribution becomes more restricted to lower latitudes. Additionally, in future projections, the proportion of suitable habitats shared by both species increases, and the overlap is especially concentrated in the future leading edge of *M. pyrifera*'s distribution. This, hence, poses another challenge for the persistence of *M. pyrifera* in the future, as *U. pinnatifida* is a highly competitive species and has already shown advantages from the disturbance of native canopy-forming kelps (Valentine and Johnson 2003, 2004). The first individuals of *U. pinnatifida* in Argentina were found attached to the port artificial substrates in Puerto Madryn, suggesting an introduction through ballast water, considering that the vegetative gametophytes of *U. pinnatifida* are capable of surviving extended periods of darkness (Dieck 1993). Therefore, *U. pinnatifida* has the dispersal ability necessary to reach regions with shared suitability with *M. pyrifera* and will likely impact the native kelp species if it becomes established in those regions. *U. pinnatifida* has been reported as progressively expanding its distribution in the Argentina coast, reducing algae diversity and richness (Casas et al. 2004) and causing changes in the food webs where it is found (Irigoyen et al. 2011b, Valiñas et al., this volume). Even considering that richness, abundance, and diversity of the flora associated with the holdfast of both kelps are similar in some areas, fauna associated to *M. pyrifera* presented higher values of these descriptors when compared with *U. pinnatifida* (Raffo et al. 2009). These results obtained in northern Patagonia suggest that community changes related to the *U. pinnatifida* invasion continue to expand.

However, it is necessary to consider that these future projections do not account for changes in dissolved oxygen, an important predictor in determining the distribution of *M. pyrifera* and *U. pinnatifida*, or phosphate concentrations, the second variable most important in describing the distribution of *M. pyrifera*. Changes in both variables that are dependent on coastal management, sewage treatment efficiency, and ocean temperature will result in modifications in the future distribution of these species, and as such, our future predictions should be considered carefully. The predicted increase in precipitation in northern Argentina (Pessacg et al., this volume) can substantially cause alterations in sediment and nutrient fluxes, leading to ecological changes (Hamilton 2010). Moreover, future trends of increasing water pollution levels in South America, related to anthropogenic nitrogen and phosphorus inputs (van der Struijk and Kroeze 2010; Liu et al. 2012), will also result in substantial impacts to marine forests in Patagonia. The population of *U. pinnatifida* from Nueva bay, at Puerto Madryn city, was demonstrated to be able to uptake the ammonium, nitrate, and phosphate levels of the near sewage outfall, indicating that it is adapted to highly eutrophic conditions (Torres et al. 2004). Therefore, in a possible scenario of increasing nutrient pollution, *U. pinnatifida* can have an advantage over native species.

The loss of canopy-forming macroalgae, such as *M. pyrifera*, can have a cascade effect on the ecosystem. Decreased canopy cover results in reduced availability of refuges close to the surface of the water, which some species of fish are dependent on. The removal of *M. pyrifera* in the Beagle channel, Tierra del Fuego, resulted in the reduction of abundance of *Paranotothenia magellanica* (a fish species of cold waters), although no change in the diversity of fishes assemblages was observed (Vanella et al. 2007). Moreover, the presence of *U. pinnatifida* on rocky reefs reduced the abundance of recreational and commercial fishes on northern Patagonia (Irigoyen et al. 2011a). Increasing delivery of waste waters and port activities has already driven the change in coastal communities of macroalgae in Puerto Madryn, with observed loss of *M. pyrifera* and increased presence of *U. pinnatifida*. Consequently, further changes in environmental conditions can lead to more alterations in macroalgae assemblages and likely affect the fish communities associated with these ecosystems (Irigoyen et al. 2011a).

The kelp forests of the southernmost tip of Patagonia are considered one of the least disturbed marine forests on the planet, mostly due to the remoteness and extreme weather of the region, which results in low population density and relatively low anthropogenic impacts (Friedlander et al. 2020). Our future projections show that the region of Tierra del Fuego will still have suitable habitats for one of its most abundant species of kelp, *M. pyrifera*, and thus this area has the potential to become a sanctuary for many marine species that depend on this ecosystem. However, as discussed extensively in this chapter, changes in species distributions and water quality, besides many other local stressors, will affect this region in the future. To maintain the status of Tierra del Fuego as one of the "last global refuges for kelp forests" (Friedlander et al. 2020) and its key roles of sustaining large populations of marine species and of spawning and nursery for fisheries species, conservation actions must be taken to preserve this ecosystem.

Further Efforts

It is necessary to consider that climate change is happening, while the human population continues to grow and may double by 2100 (Kc and Lutz 2017). Moreover, human settlement takes place unevenly on the surface of the continents, concentrating in coastal regions, in line with countless other local and global stressors (He and Silliman 2019). Climate-driven ecosystem models highlight a loss of primary production at mid-latitudes. This can trigger a bottom-up cascade effect by reducing marine biomass and likely diversity, particularly at higher trophic levels. Cumulative impacts of regional and global threats to biodiversity need to be minimized to preserve the adaptive capacity of marine ecosystems in the present and coming centuries (Worm and Lotze 2021).

From a management perspective, urbanization runoff must reduce the release of nutrients like N and P (Borja et al. 2020), and mining activities should reduce contamination of water with polluted mud (Landrigan et al. 2020). The creation of marine protected areas (MPAs), such as the national park created at northern San Jorge gulf, focusing on marine forests and considering biogeographical and regional particularities, can increase resilience of ecosystems. In addition, it is important to identify, characterize, and incorporate regions of climate refuge for foundation species and endemic taxa. In this process, especially considering tropicalization routes, it is strategic to map future habitats of neighbor flora and fauna. In a regional and eventually transnational discussion, the number, size, and disposition of MPAs should contemplate the necessary connectivity considering the myriad of biological limitations to dispersal and settlement (Wilson et al. 2020). Combining this framework that increases heterogeneity and reduces the frequency and intensity of local stressors, we can increase the adaptive capacity, reducing or stopping the loss of biodiversity.

The decreasing health of coastal areas should foster the development and eventually, application of initiatives of mitigation and restoration. Considering the current status of eutrophication in some ports and bays, the accelerated removal of nutrients promoting seaweed aquaculture can be discussed (Racine et al. 2021). Reinforcing the role of marine forest restoration on their canopies, there is an improvement of the understanding about life cycle drivers and constraints to reconstruct environments considering damages related to climate change events, natural or anthropogenic disasters (Layton et al. 2020). Finally, it is crucial to understand that the scenario responsible for the profound changes observed in marine forests is complex, and so it needs a complex and integrated approach to provide robust solutions.

To identify the root of the global system changes and to reduce planetary vulnerability, it is important to rework the socioeconomical model and concepts that have drawn the world's attention in the last decades. In this process, it was essential to recognize that the uses of natural resources imposed by humanity in the last almost two centuries changed the Earth system and were enough to circumscribe a new geological moment (Malhi 2017). However, the denomination of this recent past as Anthropocene (Lewis and Maslin 2015) sometimes is not enough to characterize the actual times (see, e.g., Sala, this volume). It is important to recognize that nations fail to use this flag in the identification of causes and in the look for solutions to the global environmental crisis. It is important to highlight that at least since the UN Stockholm Convention in 1972, nations have recognized that the origin of most threats to global biodiversity and ecosystem functioning is our socioeconomic behavior. In the last decades, science clarified that our biosphere has been primarily transformed by a particular set of socioeconomic systems, with the generation of abundant and increasing waste that contaminates the atmosphere, soil, and water (Altvater et al. 2016). Considering that among human beings, different cultures present different relationships with nature, it is important to disseminate in environmental science the challenge for new circumscription of the human activities behind the threats to our biodiversity and sustainability. In this sense, the term Capitalocene appears as complementary view to represent our age and the causes that are at the root of biodiversity crisis observed worldwide (Stuart and Guderson 2020).

Dealing with different aspects, but with the main target clearly, science and society must look for an alternative worldview with compromise with a regenerative and distributive economy. The pandemic is showing that environmental science must step back and look deeper in the causal framework of the multifactorial scenario, with all complex interactions, related to the losses of goods and services of different marine environments. By understanding the functioning of biodiversity and ecosystems, we can respond to these complex scenarios discussed in this chapter, inspiring solutions to reduce our vulnerability and resist global change challenges.

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The Impact of Global Change on Marine Benthic Invertebrates

Juan López-Gappa

Introduction

Almost six decades have passed since the pioneer studies on the ecology and structure of Patagonian intertidal assemblages were carried out (Ringuelet et al. 1962; Olivier et al. 1966b). The growing concern about global coastal changes (Valiela 2006) and the harmful effects of maritime transport of nonindigenous marine organisms (Carlton and Geller 1993) led marine ecologists to increasingly realize that few, if any, pristine coastal environments still remain on Earth (Orensanz et al. 2002). This chapter is an attempt to summarize the changes that occurred during that period of time in assemblages of coastal benthic invertebrates of Atlantic Patagonia.

The chapter begins with an overview of biogeography and latitudinal trends in the biodiversity of marine benthic invertebrates, followed by abiotic factors influencing species distribution. Special attention was paid in reviewing the main invasion events of nonindigenous species, as some of them were decisive in altering the original structure of the coastal seascape. A massive mortality episode of an intertidal beach clam is described, and its possible causes are analyzed. Finally, likely changes in the coastal invertebrate assemblages of Atlantic Patagonia in the near future are discussed. The effect of eutrophication on benthic invertebrates is briefly mentioned. Although fishing pressure is also recognized as a huge stressor to be increased in future scenarios, this issue is discussed in Narvarte et al. (this volume) and will not be considered here.

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Distribution Patterns of Intertidal and Subtidal Invertebrate Assemblages in Patagonia

Biogeography

One of the most important abiotic factors influencing the distribution of marine coastal invertebrates is water temperature. In a pioneer study, Balech (1949) highlighted the importance of water mass dynamics in the geographic distribution of the marine biota off the Argentine coast. After decades of analyzing the biogeography of marine organisms, a consensus has been achieved among marine biologists that the coastal and shelf areas off Argentina can be divided into two main biogeographic units: the Argentine and the Magellanic biogeographic provinces (Balech 1964; Bastida et al. 1992; Boschi 2000; Balech and Ehrlich 2008, among others).

The Argentine province encompasses southern Brazil, Uruguay, and the northern sector of the Argentine sea (Buenos Aires province, San Matías, San José and Nuevo gulfs) and is characterized by having relatively warm-temperate waters. The cold-temperate Magellanic province includes the southern Chilean archipelagos up to Chiloe island in the Pacific ocean, the Magellan strait, Tierra del Fuego, the Cape Horn archipelago, and the Malvinas islands. In the southern Southwest Atlantic, it occupies the whole continental shelf off Tierra del Fuego and Santa Cruz provinces. There is no agreement among the different authors about the coastal limit between both provinces. This controversy can be explained because, as in many biogeographic ecotones, the boundary between the Argentine and the Magellanic provinces is a gradual transition. The cold-temperate waters of the Malvinas current flow northward along the continental slope off Argentina up to approximately 38°S (Matano et al. 2010; Saraceno et al. this volume). The boundary between warm- and cold-temperate waters off Buenos Aires province is also a transitional one. A series of benthic stations sampled at increasing depths (30–130 m) along a transection to the southeast of Mar del Plata (Roux et al. 1988) showed that (1) samples taken at depths of 30–74 m consisted exclusively of fauna from the Argentine province; (2) samples collected at depths of 84–130 m contained fauna typically belonging to the Magellanic province; and (3) samples collected at intermediate depths (76–81 m) were composed of eurioic Magellanic species having a wide range of distribution throughout most of the Argentine continental shelf. In other words, there was an intermediate assemblage of widely distributed Magellanic species between the typically Argentine and Magellanic assemblages.

Two biogeographic studies based on a large-scale survey of the Argentine continental shelf onboard the R/V *Shinkai Maru* (López-Gappa and Lichtschein 1988; Bastida et al. 1992) arrived at similar conclusions. Two major groups were distinguished: one inhabiting the warmer inner shelf off Buenos Aires and northern Patagonia (the Argentine province) and the other occupying the colder mid- and outer shelf off Buenos Aires and most of the Patagonian shelf (the Magellanic province). They also found an intermediate assemblage that could be defined as an impoverished Magellanic fauna, distributed on relatively shallow bottoms along the

Patagonian shelf and reaching coastal areas off Santa Cruz and Chubut provinces (Bastida et al. 1992).

Latitudinal Gradients in Species Diversity

One of the most striking features of life in terrestrial ecosystems is the gradient of increasing biodiversity from the poles to the equator (Brown and Lomolino 1998; Gaston 2000). In the northern hemisphere, the richness of marine species also increases from the Arctic to the tropics (e.g., Roy et al. 1998, 2000), but this pattern seems to be absent in the Southern hemisphere (Clarke 1992). Different groups of marine benthic invertebrates show contrasting latitudinal patterns of biodiversity along the coasts of southern South America. Diversity decreases with increasing latitude in groups with planktotrophic larval stages (Astorga et al. 2003). This is the case of decapod crustaceans, which exhibit higher diversity off Buenos Aires province than in Patagonia and Tierra del Fuego (Boschi 1964). Spivak (1997) recorded 200 decapod species in the warm-temperate region of the southwest Atlantic (including Brazil and Uruguay) but just 39 species in the cold-temperate region. Vinuesa (1977) showed that the Fuegian fauna of decapod crustaceans originated in the southeast Pacific and entered the southwest Atlantic when the Drake passage opened to deep water circulation during the Eocene-Oligocene boundary (31–32 Ma, Lawver and Gahagan 2003).

On the contrary, direct developers show the opposite trend (Fernández et al. 2009). Most invertebrate phyla in the southern South Atlantic exhibit a clear pattern of increasing biodiversity with increasing latitude. This highlights the importance of considering life history attributes when analyzing the processes driving latitudinal trends of species richness. Low temperature at high latitudes might favor direct developers as the cost of brooding (e.g., oxygen provision) increases with temperature (Brante et al. 2003; Fernández et al. 2009).

Bernasconi (1964) listed much more species of sea stars and sea urchins in the Magellanic than in the Argentine assemblages. Souto et al. (2014) showed that echinoderm species richness in the Southwest Atlantic increases significantly with latitude between 34° and 56°S, with the highest biodiversity values being recorded between 46° and 56°S. In a study of the organisms associated with intertidal coralline turf, Liuzzi and López-Gappa (2008) concluded that macrofaunal species richness was significantly higher in samples from Chubut than in those from Buenos Aires province (Fig. 1).

The biodiversity of bryozoans in the Southwest Atlantic south of 35°S was summarized by López-Gappa and Lichtschein (1988) and López-Gappa (2000). A distinct diversity gradient was found, with the highest richness values occurring off Santa Cruz and Tierra del Fuego provinces, two areas dominated by coarse bottom sediments (Parker et al. 1997). Patagonian and Fuegian bryozoans are not only important in benthic assemblages; their fragments are also the dominant components of shelf biogenic carbonates in the sea bottom sediments off these two provinces (Bastida et al. 1981).

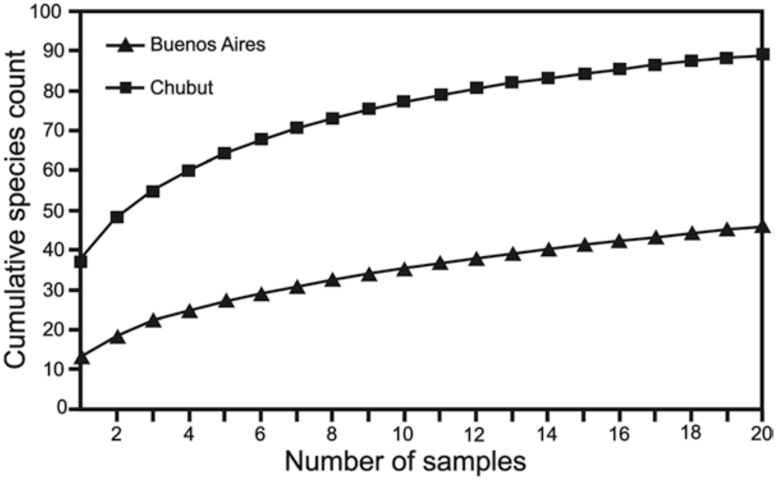

Fig. 1 Species accumulation curves of invertebrates associated with coralline turf in the low intertidal zones of Chubut and Buenos Aires provinces. Modified from Liuzzi and López-Gappa (2008)

Valdovinos et al. (2003) demonstrated that the southeastern Pacific molluskan species diversity remains relatively low in central Chile and then sharply increases toward higher latitudes. These authors proposed the hypothesis that increased shelf area south of 42°S, together with geographic isolation and the existence of refuges during glaciations, enabled a higher rate of species diversification. The increased biodiversity generated by these processes may be the likely cause of the relatively high diversity of the biota that made its way into the southern Southwest Atlantic after the opening of the Drake passage.

A biogeographic study of the benthic amphipods of the southern Southwest Atlantic showed that species richness was closely related to the sampling effort but also increased significantly with latitude (López-Gappa et al. 2006). The Argentine province was represented by 35 species, ranging from 36° to 43°S and encompassing coastal or relatively shallow shelf areas off Buenos Aires, Río Negro, and Chubut provinces. The Magellanic province was represented by 157 species, ranging from 36° to 56°S and including the coasts of Tierra del Fuego, Santa Cruz, and the Malvinas islands. The coastal transition between both faunistic assemblages occurs around 43°–44°S, and on the continental shelf, it follows a SW-NE direction around 70–100-m depth (López-Gappa et al. 2006). Similarly, an inverse latitudinal biodiversity pattern was reported for another group of peracarid crustaceans in the southern Southwest Atlantic, the asellote isopods. Species richness was found to be about six times higher in the Beagle channel and the Patagonian coast south of 47°S than north of this latitude (Doti et al. 2014).

The biodiversity of marine Porifera of Argentina in the Southwest Atlantic between 35° and 56°S is closely related to the concentration of the sampling effort: it appears to be highest in thoroughly surveyed areas, such as around Mar del Plata, Malvinas islands, and the coast of Tierra del Fuego. The biodiversity of marine sponges is weakly but significantly correlated with latitude, as stations between 50° and 55°S were on average richer than those located off Buenos Aires province (López-Gappa and Landoni 2005).

Abiotic Factors Influencing Species Distributions

Communities on Patagonian intertidal rocky shores are exposed to harsh physical conditions caused by dry, strong winds, resulting in intense desiccation of intertidal organisms (Bertness et al. 2006). Desiccation stress is more severe on wave-protected than on wave-exposed shores. Communities are therefore more strongly organized by physical stress than rocky intertidal communities previously studied in other regions of the world (Bertness et al. 2006). During low tides, predators are never found in the open (Hidalgo et al. 2007). They depend on shelter offered by foundation species such as the mussel *Perumytilus purpuratus* and coralline algae. Native predators are small and feed primarily on small, soft-bodied prey. On the contrary, the invasive green crab, *Carcinus maenas*, exhibits a much greater voracity than native predators (Hidalgo et al. 2007). As this crab preys upon *P. purpuratus*, the main structuring species affording shelter, its feeding habits could cause changes in native diversity.

The pulmonate limpet *Siphonaria lessoni* (see Güller et al. 2016) is the dominant grazer at mid- and high intertidal levels of Patagonia (Bazterrica et al. 2007). A study on limpet grazing in a dry, wind-swept rocky shore at Dos Bahías cape (San Jorge gulf, Chubut) showed that environmental harshness was determinant in this system. Grazing by *Siphonaria lessoni* had no detectable effects in the high intertidal where physical forces dominate community organization. Grazing impacts on rocky shores were relatively weak in comparison with the physical stresses that largely determined the structure (Bazterrica et al. 2007).

Severe desiccation stress was also shown in intertidal assemblages dominated by the mussel *Brachidontes rodriguezii* in Buenos Aires province. Massive bleaching and subsequent demise of intertidal algae occur during early spring, midday low tides, suggesting a strong temporal impact of desiccation stress (López-Gappa et al. 1993; Adami et al. 2004).

Water temperature has also detectable effects on physiological processes of marine coastal organisms. Synchronous shell growth increments in the bivalve *Glycymeris longior* can be employed to generate a multi-decadal chronology. This chronology can in turn be used as an environmental proxy, as it exhibits a significant positive correlation with changes in sea surface temperature (Gimenez et al. 2020).

It has been shown that barnacles living higher on the shore are more tolerant to high temperatures and more resistant to desiccation (Foster 1971a, b). Laboratory experiments with adult *Amphibalanus amphitrite* from a sewage-impacted site in Buenos Aires province showed that this species is very tolerant to desiccation stress (Calcagno and Luquet 1997).

Eutrophication and Sewage Pollution

The response of macroalgae and invertebrates to eutrophication was experimentally evaluated in San Antonio bay, a macrotidal coastal system in northern Patagonia (Martinetto et al. 2010, 2011; Teichberg et al. 2010). Macroalgae and small infaunal and epifaunal invertebrates were more abundant and diverse in a channel where nutrient concentrations were higher. The intense flushing during the semidiurnal macrotidal cycle prevented anoxic or hypoxic events, making the environment suitable for consumers by increasing food availability (Martinetto et al. 2010). Large water exchanges during tidal cycles decreased the negative effects of macroalgal accumulation, enabling herbivore invertebrates (chitons, limpets) to have a large impact on macroalgae (Martinetto et al. 2011). Another study in the same area showed that under higher nutrient and grazer conditions, natural benthic succession not only differs in trajectory but in its final taxa composition, promoting higher biodiversity and biomass accumulation (Fricke et al. 2016).

The effect of the Puerto Madryn sewage discharge on intertidal macroalgae and invertebrates was assessed in Nuevo gulf, by comparing the benthic assemblages before and after the outfall was removed. A distinct change in species composition was detected: impacted and control sites were neatly separated in the multivariate analysis, while the sewage discharge was operational, but no such distinction persisted after the elimination of the outfall (Torres and Caille 2009).

Changes Observed in Coastal Assemblages in the Last Decades: Introduction and Spread of Nonindigenous Benthic Invertebrates

In the following sections, the most important cases of invasive invertebrates recorded in the benthic coastal communities of Argentine Patagonia are described and analyzed.

Nonindigenous Species in Patagonian Fouling Assemblages

Ocean shipping is regarded as the most important vector for transoceanic transport and introduction of species across biogeographic boundaries (Drake and Lodge 2007). A survey of 194 commercial vessels arriving at five Argentine ports (four of them on the Patagonian coast) between July 2007 and December 2008 showed that compliance with national and international regulations and guidelines on ballast water management is poor in the area (Boltovskoy et al. 2011). Although ports in Buenos Aires province were exhaustively surveyed since the 1960s (Bastida 1971, among others), just a brief summary of the fouling assemblages of Puerto Madryn was the only available information about this subject in Patagonia during decades

(Bastida 1973). Marine fouling organisms in Patagonian ports were later analyzed in a large-scale study that surveyed mobile and sessile taxa from San Antonio Este to Ushuaia (Schwindt et al. 2014). This survey found 247 fouling species, including 17 introduced taxa and other 15 species currently regarded as cryptogenic, i.e., needing further study to clarify their status. As the original list of taxa known for Puerto Madryn (Bastida 1973) consisted almost exclusively of native species, the Patagonian survey (Schwindt et al. 2014) showed that significant changes occurred in Patagonian fouling assemblages during the last decades. A recent comprehensive survey of marine bioinvasions in the southern Southwest Atlantic (Schwindt et al. 2020) added 100 new introduced and 43 new cryptogenic species. Of these 100 species, 33 were new invasions that occurred since 2002, averaging a new invasion every 178 days.

The composition, recruitment, succession, and the effect of consumers on the macrofouling assemblages of Comodoro Rivadavia harbor were analyzed by Rico and López-Gappa (2006) and Rico et al. (2010, 2012, 2016). The invasive barnacle *Balanus glandula* was the most abundant species in the middle intertidal (Rico and López-Gappa 2006). The fouling assemblage consisted of algae, spirorbid polychaetes, compound ascidians, hydrozoans, bryozoans, and fish egg masses. Fouling assemblage structure differed significantly between upper and lower surfaces: filamentous algae were dominant on upper surfaces, while filter-feeding invertebrates were more abundant on the lower surfaces of experimental panels (Rico et al. 2010). Temporal changes in diversity depended on substrate orientation. On the lower surfaces, diversity reached a maximum after 9 months and then declined, mainly due to the extensive dislodgment of two species of ascidians. On algal-dominated upper surfaces, differences in the structure of annual assemblages were due to seasonal changes in the abundance of ephemeral algae (Rico et al. 2012). Large predators exerted a significant effect on assemblage structure and diversity, indirectly promoting the development of filamentous algae and mesoherbivores by controlling the abundance of browsers (Rico et al. 2016).

Ascidians

The arrival of the solitary ascidian *Ascidiella aspersa* was detected in Patagonian harbors and natural areas since the early 1960s. The species is now distributed over 10 latitudinal degrees in harbors and subtidal areas along the Southwest Atlantic (Tatián et al. 2010). *A. aspersa* forms dense aggregations at El Sótano (San Matías gulf), serving as substrate to the native mytilid *Musculus viator* (Lazari et al. 2018).

The clubbed tunicate *Styela clava* is estimated to have arrived in San Antonio bay in 2010 (Pereyra et al. 2015). It is considered to be native to Japan, Korea, northern China, and the Russian Federation in the NW Pacific, but it has spread globally over the last 80 years (Goldstien et al. 2011). It can dominate the fouling communities and causes great concern due to the ecological and economic damages it can cause at high densities (Wong et al. 2011). The presence of *S. clava* promotes the recruitment of the invasive kelp *Undaria pinnatifida* probably by increasing habitat complexity and providing refuge from grazers (Pereyra et al. 2017).

Oysters

The origin of the invasion of *Magallana gigas* (formerly *Crassostrea gigas*) can be traced back to 1982, when a fisheries company brought oysters to San Blas bay with the intention of starting an oyster culture (Orensanz et al. 2002). The culture operation was interrupted after a few months, and the oysters were abandoned (Pascual and Orensanz 1996). The presence of adult specimens of *M. gigas* was later confirmed in beaches of San Blas bay, suggesting the existence of an established population. The first appearance of a Pacific oyster bed occurred in January 1994 near San Blas (Borges et al. 2002). The species is expanding its range outside the original area of introduction, to the north (Dos Santos and Fiori 2010) and to the south (Castaños et al. 2009). The dispersion path of *M. gigas* larvae from San Blas to Río Negro province was recently modelled based on longshore current intensities (Wörner et al. 2019). Oysters were afterward transplanted for experimental aquaculture to Caleta Olivia, San Julián, and Río Gallegos, but no invasion of natural ecosystems had been detected there until 1999 (Orensanz et al. 2002). *M. gigas* postlarvae settle on the mussel *Brachidontes rodriguezii* and may build reefs when settling on sandstone and sediments in Anegada bay (Fig. 2, Borges

Fig. 2 Reef formed by the Pacific oyster *Magallana gigas*, in Anegada bay, Buenos Aires province. Photograph by Mónica Borges

2005). Anegada bay has been regarded as a well-documented case of an introduction site where optimal environmental conditions are met, both for complete gonad maturation and for successful larval survival and settlement (Castaños et al. 2009). Twenty years after the introduction of *M. gigas* to northern Patagonia, satellite imagery and field and aerial inspections revealed the presence of ten oyster beds at the intertidal zone of Anegada bay (Escapa et al. 2004). These structures brought about noticeable changes in benthic community structure. Most epifaunal organisms showed higher densities inside than outside oyster beds, probably as a result of increased habitat structure and refuges. The densities of bird species were also higher inside oyster beds compared with similar zones without oysters (Escapa et al. 2004). Mendez et al. (2015b) also showed that *M. gigas* has a critical role in the invaded environments through the provision of microhabitats and settlement substrates for the sessile species. Oysters can also affect near bed flows and sedimentation processes, and their filter-feeding activity can decrease turbidity and increase light penetration in the water column (Ruesnik et al. 2005). In addition, the invasion of the Pacific oyster caused the appearance of a pathogen: the *Ostreid herpesvirus 1* has recently been identified in a wild population of *M. gigas* in Argentina (Barbieri et al. 2019).

The occurrence of natural recruitments of a second invasive oyster species in Samborombón bay, Buenos Aires province, highlights the great invasive capability of these organisms (Giberto et al. 2012, but see Lomovasky et al. 2014). There, oyster spat becomes attached to the basal part of *Spartina alterniflora* stems, increasing the mortality rate of this cordgrass (Lomovasky et al. 2014). Phylogenetic analyses based on mitochondrial and nuclear sequences identified this nonindigenous oyster at Samborombón bay as *Talonostrea talonata*, a species described for China and recently found from northern Brazil to Argentina (Cavaleiro et al. 2019). The great ecological plasticity of this species makes it a major threat to oyster culture in the area. It seems likely that its expansion may continue southward, toward the north Patagonian gulfs.

The Green Crab **Carcinus maenas**

One of the main changes that occurred in the Patagonian intertidal was the appearance of an important predator of hard-shelled prey. *Carcinus maenas* (Fig. 3) is a decapod crustacean native to Atlantic Europe and perhaps northwest Africa (Carlton and Cohen 2003). It can live and reproduce under brackish water conditions (Anger et al. 1998). The species was likely transported by ships and established successfully in five temperate regions outside of its native Europe. A previous study based primarily on a literature analysis and examination of museum specimens predicted that its potential distribution range included the Atlantic coast of Argentina (Carlton and Cohen 2003). The prediction came true, and in November 2003 and January

Fig. 3 The green crab *Carcinus maenas*, at Dos Bahías cape, Chubut, 2005. Photograph by Fernando Hidalgo

2004, populations of *C. maenas* were found in three localities of Chubut province: Camarones (Hidalgo et al. 2005), Comodoro Rivadavia, and Rada Tilly (Vinuesa 2005). Crabs were collected from the intertidal zone and the upper sublittoral fringe (Vinuesa 2007). In June 2007, the population encompassed the entire San Jorge gulf (Ledesma et al. 2010) and was later reported in Nuevo gulf since 2015 (Torres and González-Pisani 2016). The analysis of its size frequency distribution suggested that the species had been introduced at least 3–4 years before its detection in the Patagonian coast. Crab's claws are specialized structures used to crush their preys. Geographic variation in claw-crushing forces has been demonstrated in geographically separated populations of this invasive crab (Taylor et al. 2009). Carapaces accumulated on the intertidal can be sexed using geometrical morphometry (Ledesma et al. 2010).

The diet of *C. maenas* was studied at Nuevo gulf using direct stomach observation, stable isotope analysis, and metabarcoding of their preys. The green crab at Nuevo gulf has a very broad diet: its main prey items are mytilid bivalves, but algae, annelids, fish, echinoderms, and peracarid crustaceans were also identified in the gut content (Cordone et al. 2020). Laboratory feeding trials showed that *C. maenas* preyed upon almost all the preys offered, with no preferences for the species consumed (Hidalgo et al. 2007). Experimental studies will be necessary to assess the effects of *C. maenas* on the intertidal community structure of coastal Patagonia.

The Shrimp Palaemon macrodactylus

The invasive shrimp *Palaemon macrodactylus* was collected for the first time in Mar del Plata harbor in March 2000 (Spivak et al. 2006). This estuarine species is native to Northeast Asia but has been reported as introduced in Australia, Europe, and the Atlantic and Pacific coasts of the United States (Ashelby et al. 2013). In Mar del Plata, its estimated life span is about 1 year, and the sex ratio is biased to females (Vázquez et al. 2012). Its larval stages are able to survive and reach the juvenile phase at salinities between 12 and 32 (Vázquez et al. 2015). Later surveys showed that *P. macrodactylus* is expanding its distribution toward the north and the south, including new brackish water areas such as Samborombón bay and Bahía Blanca. Its southernmost record in Argentina is the Negro river estuary in northern Patagonia (Martorelli et al. 2012). This shrimp has an omnivorous diet, including benthic items such as barnacles, polychaetes, and small bivalves (Ashelby et al. 2013).

The Sea Slug Pleurobranchaea maculata

Since 2009, Farias et al. (2015) recorded the sudden outbreak of a neurotoxic side-gilled sea slug of the genus *Pleurobranchaea*. It first appeared in Mar del Plata port and was later found off the coast of Buenos Aires province and also in Puerto Madryn, located approximately 1200 km away from the first finding. The specific identity of this sea slug was later confirmed by genetic barcoding as *P. maculata* (Farias et al. 2016). *P. maculata* is native to Australia and New Zealand and is a vector of two potent neurotoxins (Farias et al. 2019) that can be lethal for domestic pets (Battini 2016). The only sea slug of this genus previously known for Argentina was *P. inconspicua*, a species represented just by a few specimens from museum collections (Muniain et al. 2006). Pleurobranchs are voracious predators, so that outbreaks often have a direct negative effect on local prey species. The diet of *P. maculata* in Nuevo gulf is mainly composed of sedentary polychaetes, compound ascidians, and algae (Bökenhans et al. 2018). The species has many of the traits described for successful invaders, such as fast generation times, hermaphroditism, planktotrophic larvae with long development in the water column, and a fairly omnivorous diet (Farias et al. 2016). *P. maculata* tolerates a broader range of environmental conditions in its invasive area than in its native environment (Battini et al. 2019). The invasion success of *P. maculata* may be related to the absence of native predators that recognize this sea slug as a prey and can control its abundance or spread (Battini et al. 2021).

Intertidal Barnacles

The most conspicuous change observed in the last decades in the coastal benthic communities of Argentina was the appearance of a dense upper intertidal belt dominated by a nonindigenous acorn barnacle. Pioneer ecological studies of rocky shores in Patagonia (Ringuelet et al. 1962; Olivier et al. 1966b; Zaixso and Pastor 1977) and Buenos Aires province (Olivier et al. 1966a; Penchaszadeh 1973) showed an intertidal zone dominated by mytilid bivalves and algae but devoid of a barnacle belt. Several species of native barnacles are abundant, however, at the intertidal level of the Beagle channel (Zaixso et al. 1978) and also occur on rocks at the low intertidal on the Atlantic coast of Tierra del Fuego (Calcagno and Lovrich 2000).

Cuevas et al. (2006) carried out a direct comparison of the changes that occurred in a Patagonian intertidal rocky shore after a period of 37 years. In the summer of 1962–1963, Olivier et al. (1966b) performed an ecological study at Pardelas point, Chubut, where they described the vertical distribution of benthic invertebrates and algae on the intertidal rocky shore. For comparison purposes, during March 2000, Cuevas et al. (2006) repeated the same sampling scheme of Olivier et al. (1966b) in the same Patagonian locality. The main changes they detected were as follows:

(1) The upper intertidal is now dominated by a belt of the invasive barnacle *Balanus glandula*, a species that was absent in the 1960s.
(2) The pulmonate limpet *Siphonaria lessoni* was displaced by *B. glandula* from the primary substrate. The limpets were formerly found in mobile aggregations on the rock, but after the invasion of *B. glandula*, they browse over the barnacle surfaces.
(3) Another striking change was the appearance of a mid-intertidal belt dominated by the warm-temperate mussel *Brachidontes rodriguezii*, which was apparently absent in the 1960s. The southern distribution limit of *B. rodriguezii*, a typical member of the Argentine province (Adami et al. 2004, 2018; Van der Molen et al. 2013), was San José gulf in the sixties, but it reached up to Caleta Olivia in Santa Cruz province (47°26′47″S) in 2000 (Cuevas et al. 2006).
(4) *Perumytilus purpuratus*, a small mussel characteristic of the Magellanic province, formerly dominant at the intertidal level, became restricted as a subdominant species at the low intertidal zone.
(5) The mussels *Mytilus edulis* and *Aulacomya atra*, formerly abundant at the low intertidal, became almost restricted to the sublittoral zone. According to Cuevas et al. (2006), the displacement of *S. lessoni* by *B. glandula* from the primary substrate is the result of spatial competition processes.

The presence of the nonindigenous *Balanus trigonus* in Argentina is known at least since the early twentieth century when it was found on the flat oyster, *Ostrea puelchana*, in San Matías gulf (Lahille 1910). The species had been introduced by maritime transport in southern Brazil in the 1860s, probably from the Pacific ocean (Zullo 1992). It is part of the fouling assemblage of Mar del Plata port since the

1960s (Bastida 1971; Spivak et al. 1975; Spivak and L'Hoste 1976) but has not been found in other Argentine harbors or natural areas since then.

The introduction of *Amphibalanus amphitrite* to harbor areas in Argentina probably occurred in the 1960s, as the species was not mentioned in the pioneer study of Lahille (1910). It was found in the fouling assemblages of Mar del Plata (Bastida 1971; Spivak et al. 1975; Spivak and L'Hoste 1976) and other harbors in Buenos Aires province (Orensanz et al. 2002; Spivak 2005). It was also found by Spivak (2005) in the intertidal zone of San Blas bay, but does not make up intertidal belts in Patagonia. The growth, spatial pattern, population dynamics, and production of a low-density population of this species have been analyzed in Quequén, Buenos Aires province (López-Gappa et al. 1997; Calcagno et al. 1997, 1998).

Balanus glandula is one of the most successful marine invaders in Argentina. The invasion of this barnacle spans 17° of latitude in Argentina and has completely reshaped the native intertidal landscape (Schwindt 2007). The species is native to the northwest coast of North America and arrived to Mar del Plata harbor probably by maritime transport in the 1970s (Spivak and L'Hoste 1976; Orensanz et al. 2002; Spivak 2005). It now forms a dense belt of up 5000 ind. m^{-2} in the upper intertidal (Penchaszadeh et al. 2007). Its spread rate along the Argentine coast was estimated in 244 km $year^{-1}$ (Schwindt 2007). The species was first detected in San José gulf in 1983/1984 and in Nuevo gulf in 1986 (Gomez Simes 1993). This barnacle was one of the organisms settling on artificially denuded quadrats in San José gulf since 1989 (Sánchez and Zaixso 1995). *B. glandula* was the most abundant macrobenthic organism at the mid-intertidal level within Comodoro Rivadavia harbor in 1998 (Rico and López-Gappa 2006). A belt of *B. glandula* was found on natural habitats of Comodoro Rivadavia between 2000 and 2001. The barnacles were found both on sedimentary rock and on shells of the mytilid *Perumytilus purpuratus* (Lanas and Rico 2005). A survey of the fouling assemblages in ports of Patagonia performed between 2005 and 2007 detected the presence of *B. glandula* in San Antonio Este, Puerto Madryn, and Puerto Deseado (Schwindt et al. 2014).

Ecosystem Engineers

Ecosystem engineers are organisms that directly or indirectly control the availability of resources to other organisms by causing physical changes in biotic or abiotic materials (Jones et al. 1994, 1997; Gutiérrez et al. 2003). Invasive species can interact positively with local communities by increasing the richness or abundance of some species. *Brachidontes rodriguezii* mussels with epibiotic *B. glandula* show a higher prevalence of the red alga *Porphyra* sp. than mussels without barnacles, suggesting the occurrence of a fouling cascade where barnacle epibiosis on mussels facilitates subsequent algal fouling (Gutiérrez and Palomo 2016). *B. glandula* has successfully colonized soft-bottom salt marshes (Schwindt et al. 2009), acting as an ecosystem engineer where hard substrates are a limiting resource (Mendez et al. 2015a). In this habitat, it is found on more than ten types of substrates, particularly mussel shells and the halophyte *Sarcocornia perennis* (Mendez et al. 2013). The cordgrass *Spartina densiflora*, a native ecosystem engineer, has a positive effect on *B. glandula* by trapping mussels, shells, and gravels where the barnacle settles among its stems (Sueiro et al. 2013). *B. glandula* is also found on the entire dorsal and lateral surfaces of the crab *Neohelice granulata* in a Patagonian saltmarsh (Mendez et al. 2014). Changes in the structural complexity generated by *B. glandula* facilitate the presence of other invertebrates and affect community structure by providing settlement substrates (Mendez et al. 2015a). Secondary succession leading to the recovery of mussel beds in Chubut province seems to be entirely dependent on habitat amelioration provided by the native ecosystem engineer *Perumytilus purpuratus* (Bertness et al. 2006). With the exception of mussel recruits settling in the interstitial spaces between the exotic barnacle *B. glandula*, mussel recruits are found exclusively in established mussel beds. In the mid-intertidal, where physical stress is relatively high, mussels engineer microhabitats, increase moisture retention and can provide refuge space on otherwise smooth rocks, with 43 out of 46 species obligated to living within the matrices of mussels for protection from potentially lethal desiccation stress (Silliman et al. 2011). In the lower intertidal, native organisms are also dependent on beds of another ecosystem engineer, coralline algae, for shelter from desiccation (Hidalgo et al. 2007; Liuzzi and López-Gappa 2008).

The size of *B. glandula* increases with latitude, but its density and cover do not follow a latitudinal trend. Both variables show a bimodal pattern, with maximum values at Puerto Lobos and Bustamante bay (Schwindt 2007). A molecular study showed that the source of the Argentine populations of *B. glandula* was California (Geller et al. 2008). At lower latitudes, the species recruits in winter, while at higher latitudes, it recruits in spring and summer (Rico et al. 2001; Schwindt 2007). Its shells favor the recruitment of conspecifics via provision of proper substrates for larval settlement, highlighting the importance of the physical structure supplied by this species on its own persistence within invaded soft-bottom salt marshes (Mendez et al. 2017).

B. glandula is able to successfully outcompete mussels from upper intertidal levels exposed to wave action at Mar del Plata (Vallarino and Elías 1997; Elías and Vallarino 2001). An experimental study carried out in Nuevo gulf, combining different substrate hardness and texture and two intertidal heights, showed that the highest density of adults and recruits occurs in soft-rough substrates and in the high intertidal (Savoya and Schwindt 2010). The native gastropod predator *Trophon geversianus* successfully consumes *B. glandula* in Patagonian rocky shores but exerts little top-down control on this invasive barnacle (Pio et al. 2019).

Massive Mortality of the Yellow Clam *Amarilladesma mactroides*

Amarilladesma mactroides (formerly *Mesodesma mactroides*, see Signorelli 2019) is an intertidal clam typical of sandy beaches of Buenos Aires province (Olivier et al. 1971; Bastida et al. 1991). Its southern distribution limit reaches Jabalí island, into Anegada bay, in northern Patagonia (Fiori and Morsán 2004), with occasional specimens found also at Las Grutas, Río Negro province (Olivier and Penchaszadeh 1971). The comparison between surveys performed in 1968 (Olivier and Penchaszadeh 1971) and 1989 (Bastida et al. 1991) showed a sharp decrease in the frequency of specimens of commercial size due to extraction by tourists. Climate change influenced the abundance and size of *A. mactroides* along the Uruguayan coast. Clam abundance was inversely related to variations in sea surface temperature anomalies (SSTA), with higher abundance during cold periods. The prevalence of body abnormalities was positively correlated with increasing SSTA, suggesting a link with climate stress (Fig. 4) (Ortega et al. 2016). The analysis of 23 years of clam abundance data, together with SSTA, salinity, and wind stress along the Uruguayan Atlantic coast, showed that the best scenario for high abundance of *A. mactroides* is characterized by cold and salty waters and onshore winds (Manta et al. 2017). Since the mid-1990s, the population experienced massive mortalities along Atlantic South American exposed sandy beaches (Fig. 5) (Fiori et al. 2004; Dadon 2005). Mortality events occurred sequentially in a north-south direction (Brazil-Uruguay-Argentina). One of the consequences of these events was an increase in the population of the wedge clam, *Donax hanleyanus* (Dadon 2005), and a dramatic decrease in the number of individuals of *A. mactroides* per square meter (Herrmann et al. 2011). The yellow clam population located to the south of Jabalí island was decimated by a sudden massive mortality in the summer of 2002 (Fiori et al. 2004). In a first study, no abnormalities were found in the physicochemical parameters that could justify the mass mortality (Fiori and Cazzaniga 1999), but later analyses suggested that the clams suffered a punctual process of acute pollution (Thompson and Sánchez de Bock 2007). Detailed histological analyses in a relict population from Jabalí island revealed the presence of four parasitic or commensal taxa: *Trichodina* sp. ciliates, coccidians, gregarines, and turbellarians (Cremonte and Figueras 2004, Fiori et al. 2004). Histopathological studies carried out in 2011 in individuals from Rio Grande do Sul, southern Brazil, showed that 100% of the clams analyzed were parasited by *Rickettsia* colonies (Carvalho et al. 2013). On the contrary, histological studies carried out in Buenos Aires province and Rio Grande do Sul did not find a clear pattern between the prevalence and intensity of infection and mortality events (Vázquez et al. 2016). Although synergistic effects between pollution and parasitism cannot be discarded, the wide geographic range of the mortality events suggests that parasites were its most probable cause.

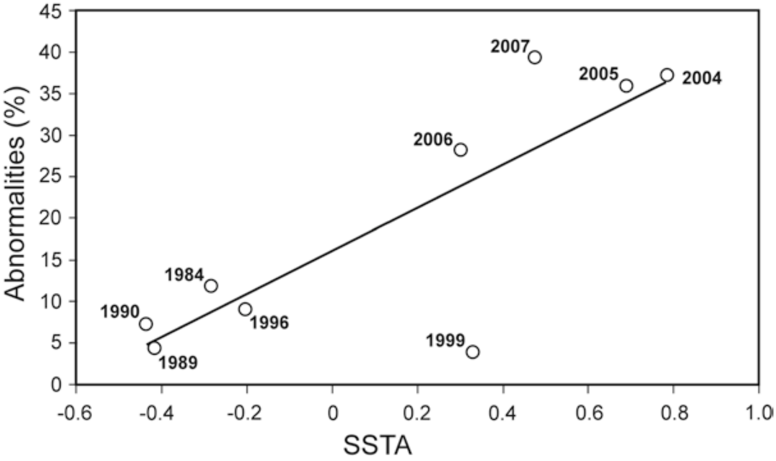

Fig. 4 The relationship between the relative occurrence of body abnormalities in the yellow clam *Amarilladesma mactroides* and sea surface temperature anomalies (SSTA). The regression ($y = 25.9\ x + 16.1$, $R^2 = 0.67$) is significant ($p < 0.001$). Redrawn from Ortega et al. (2016)

Fig. 5 Massive mortality of the yellow clam *Amarilladesma mactroides*, at Monte Hermoso, November 1995. Photograph by Sandra Fiori

Future Perspectives

At a global scale, a sea temperature rise of 3–6 °C is forecasted by the end of this century because of elevated levels of atmospheric carbon dioxide (Wang 2014). The warming, however, is predicted to be more prominent in the Northern Hemisphere, especially in the North Atlantic (Rhein et al. 2013). The sea surface temperature change in the Patagonian shelf has been estimated in 0.06 °C/decade by Rivas (2010) and in 0.08 °C between 1982 and 2006 by Belkin (2009).

A southward shift rate of ca. 9 km. year^{-1} of the 20 °C isotherm (a proxy of tropical waters) was estimated for the period 1984–2007 in the Southwest Atlantic (Ortega et al. 2016). The most important change to be expected in the Argentine coast as a consequence of sea temperature rise is the southward shift range of warm-temperate species. Photoreception mechanisms adapted to ancestral photic environments, however, may restrict range-shift capacity, resulting in photic barriers to poleward range expansions (Huffeldt 2020). The first symptoms of southward range shifts can already be perceived. The San Jorge gulf has been traditionally included in the Magellanic province, with a clear influence of cold-temperate waters (e.g., Boschi 2000). However, the increase in water temperature has been proposed as the probable cause of the recent southward range shifts observed in the distribution of several warm-temperate decapod crustaceans previously recorded up to 43°–44°S (Vinuesa 2005). Similarly, recent records of sub-Antarctic lithodid crabs in deeper waters off the Antarctic continental slope raise the possibility that crustacean decapods may be able to reconquer the Antarctic as a consequence of present and future climate changes (Thatje et al. 2005).

Caution should be exercised, however, as not all species react as predicted. For instance, the large-scale range shift experienced by the invasive mussel *Mytilus trossulus* on the coast of California was in the opposite direction as that predicted by the global warming hypothesis (Hilbish et al. 2010).

As models of air temperature predict that South America is very likely to warm in the twenty-first century (Marengo et al. 2012), the intense desiccation stress showed for intertidal communities on Patagonian rocky shores (Bertness et al. 2006; Bazterrica et al. 2007; Hidalgo et al. 2007) can be expected to get worse in the next decades.

The anthropogenic CO_2 ocean uptake and its reaction with seawater are the primary causes of ocean acidification (Duarte et al. 2013; Orselli et al. 2018), with potential deleterious consequences to marine invertebrates with calcareous skeletal structures. A reduction of −0.0010 pH units year^{-1} has been estimated for the Patagonian shelf and shelf-break zones, a strong CO_2 sink region in the global ocean (Orselli et al. 2018). In coastal areas, however, seaweed aquaculture has the potential to mitigate the effects of lower pH levels on the associated fauna (Duarte et al. 2017; Sondak et al. 2017). Studies on the effect of ocean acidification on calcareous organisms (e.g., Smith 2009; Lombardi et al. 2010; Taylor et al. 2016, among others) have yet to be undertaken with the Patagonian benthic invertebrate fauna.

As ships are the most likely vector of marine bioinvasions in the southern Southwest Atlantic, Schwindt et al. (2020) forecast that new introductions will continue until regional and international regulations to control ballast water and hull fouling begin to be effective.

The sudden irruption of the invasive bryozoan *Membraniporopsis tubigera* in exposed sandy beaches of Brazil (Espírito Santo to Rio Grande do Sul) and Uruguay (La Coronilla) was reported by Gordon et al. (2006) and López-Gappa et al. (2010). The massive amounts of colonies cast ashore after storms negatively affected the recreational use of sandy beaches. The species is dispersed by planktotrophic larvae capable of surviving relatively long periods in the water column. *M. tubigera* was originally described from Puerto Rico, Texas, and Florida (Osburn 1940), but it is also possible that it may even not be native to these areas, given that it was not known there prior to the 1940s and its congeneric species are east Asian (Liu et al. 1999). Its known geographic distribution suggests that *M. tubigera* could thrive in tropical and warm-temperate coastal waters worldwide. The thermal affinities among southern Brazil and Uruguay and the warm temperate coast of Argentina (Guerrero and Piola 1997) suggest that the invasion of *M. tubigera* could proceed southward in the future, at least up to San Matías and San José gulfs in northern Patagonia (López-Gappa et al. 2010).

The invasive capability of a species usually depends on the range of abiotic factors that it can tolerate in its native and invaded regions. In view of the wide temperature range that *Balanus glandula* can withstand, Schwindt (2007) has predicted that the entire South American coastline could be colonized by this species in the future.

Bioclimatic modelling is now possible due to the availability of marine data layers. Benthic layers for temperature, salinity, nutrients, chlorophyll, and other key environmental variables contained in databases like Bio-ORACLE (Assis et al. 2018) and MARSPEC (Sbrocco and Barber 2013) may be of great value in forecasting future invasions in Patagonia.

Changes in the geographic distribution of marine species on the North American continental shelf have been modelled using long-term ecological survey data. Future shifts in species distributions were generally poleward and followed the coastline (Morley et al. 2018).

Ecological niche modelling based on surface seawater and atmospheric temperatures was used to predict the potential range of distribution of the invasive oyster *Magallana gigas* (Carrasco and Barón 2010). The geographic limits of distribution predicted by this analysis for the southwest Atlantic coast were Paranaguá (25.7°S, Brazil) and the Ría of Puerto Deseado (47.7°S, Patagonia). A field experiment conducted to test oyster recruitment success on rocks translocated from the most representative geological formations present in intertidal outcrops along the coast of Patagonia showed that pelitic mudstone was the preferred substrate for Pacific oysters (Fig. 6). The Valdés peninsula and the central San Jorge gulf, where these outcrops are the dominant intertidal hard substrate, are the regions with highest potential for *M. gigas* intertidal reef formation in the future (Carrasco et al. 2019).

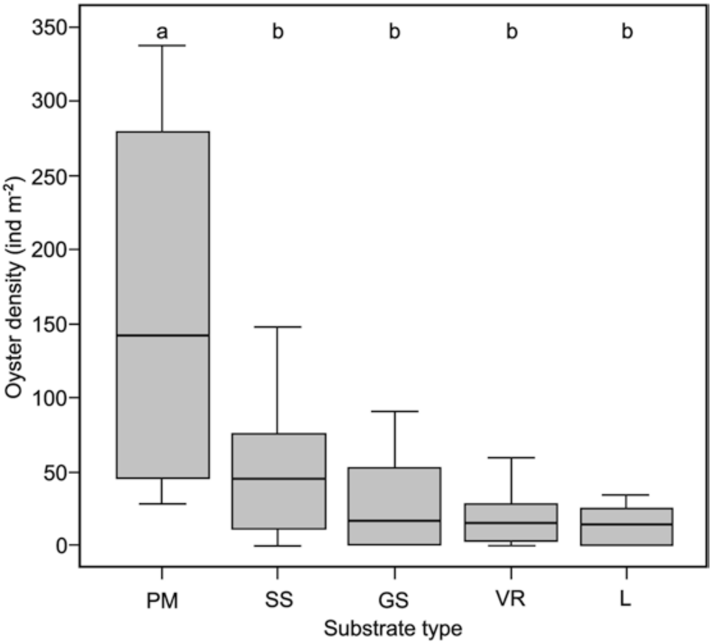

Fig. 6 Densities of *Magallana gigas* in different substrate types. *PM* pelitic mudstone, *SS* polymictic sabulite sandstone, *GS* gray sandstone, *VR* volcanic rock, *L* limestone. Substrates marked with the same lowercase letter (above) do not differ significantly. Redrawn from Carrasco et al. (2019)

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Changes in the Specific and Biogeographic Composition of Coastal Fish Assemblages in Patagonia, Driven by Climate Change, Fishing, and Invasion by Alien Species

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Anthropogenic Causes of Global Change and Fishes

Coastal environments are the marine systems with the most significant interactions between the natural environment and society and the most complex and dynamic. Coastal fish assemblages support and provide a diversity of ecosystem services like food provisioning by commercial fisheries at different scales and recreation by diving, sport angling, and spearfishing. Although human populations rely on these systems and on their biological resources to survive and maintain economies alive, growing human-induced pressures such as climate change, CO_2 enrichment, fisheries, biological invasions, pollution, and land use have profound and diverse consequences on them, with significant repercussions for society (Marquet et al. 2018; Bezerra et al. 2019; Sage 2020).

Climate change is projected to affect the fitness of organisms during all life stages, thereby impacting the size and structure of their populations, species community composition, and ecosystem functioning (Pörtner and Knust 2007; Bryndum-Buchholz et al. 2019). These impacts on organisms may be direct, through the effect of temperature, hypoxia conditions, ocean acidification, and climate-induced shifts in hydrodynamics and sea level, or indirect and mediated through shifts in the structure of food webs or by spatial and temporal fluctuations in food availability (see Fig. 1; Pörtner et al. 2007). As environmental conditions shift, organisms initially react based on physiological and behavioral responses shaped through their evolutionary history (Somero 2012). Behavioral responses mainly include the avoidance of unfavorable conditions and movement into more suitable areas (McHenry et al. 2019; Fredston-Hermann et al. 2020). New conditions may be physiologically tolerable, allowing acclimatization through several molecular to systemic adjustments of functional capacities (Pörtner 2002) or by promoting adaptation, due to the increased abundance and reproduction of existing heat-tolerant genotypes (Parmesan 2006). Conversely, new conditions may be intolerable, promoting migration of individuals or populations and local extinction if adaptation is impossible (Cheung et al. 2009).

Temperature is the most pervasive abiotic factor governing an organism’s biology (Beitinger and Lutterschmidt 2011). The temperature defines the large-scale geographical distribution of aquatic animals in the oceans, within conditions set by geomorphology, ocean currents, water depth, and stratification or salinity (Pörtner and Peck 2011; McHenry et al. 2019). Thus, the thermal sensitivity of organisms is a fundamental factor resulting in climate-induced changes in marine ecosystems (Pörtner and Farrell 2008). Temperature limitations of aquatic ectotherms are hypothesized to be set mainly by aerobic scope reductions, defined as the difference between standard and maximum metabolic rates. The reduction in aerobic scope is caused by the limited capacity of circulatory and ventilatory systems to satisfy oxygen demand under increased or decreased temperatures (oxygen and capacity-limited thermal tolerance (OCLTT) hypothesis) (Pörtner 2002; Pörtner and Farrell 2008). The difference between upper and lower critical temperatures (which characterizes the onset of the anaerobic metabolism), i.e., the thermal window of marine fishes, might be very different between life stages, being larvae more sensitive than juveniles and adults (Komoroske et al. 2014; Moyano et al. 2017), and also among species (Beitinger et al. 2000). In general, species with similar, but not necessarily identical, thermal windows will coexist. This fact would explain why climate sensitivity differs among species and would be one of the main reasons for climate-induced changes in community composition and food web interactions (Pörtner and Peck 2011). The thermal windows also vary with latitude, being narrowest in fishes from high and low latitudes and widest in fishes from intermediate latitudes (Pörtner 2002; Pörtner and Peck 2011). Moreover, in the context of climate change, the difference between the upper thermal limit and the climatological temperature of the organism's habitat (i.e., warming tolerance) represents an essential characteristic of ectotherms because it approximates the amount of environmental warming they can tolerate before their performance drops to fatal levels (Deutsch et al. 2008). In this sense, warming tolerance is higher for temperate fish species than for tropical fishes, thereby confirming that species with the highest thermal limits have the lowest warming tolerance (Vinagre et al. 2016).

In a climate change context, temperature variations cooccur with increasing hypoxia events due to the enhanced stratification of water bodies and elevated O_2 demand of organisms in the warming seas (Breitburg et al. 2018), as well as with progressive CO_2 accumulation, leading to scenarios of ocean acidification (Caldeira and Wickett 2005). In waters deeper than the surface mixed layer, hypoxic conditions and elevated CO_2 levels enhance the sensitivity of fishes to thermal extremes by reducing tissue functional capacities, including those involved in oxygen supply (Pörtner et al. 2005). Consequently, their thermal windows narrow, suggesting a considerable sensitivity of their width to warming and CO_2 and O_2 contents (Pörtner 2010). Empirical evidence for different taxa supports this idea. For instance, Dahlke et al. (2017) investigated CO_2-driven ocean acidification effects on embryonic thermal sensitivity and performance in the Atlantic cod, *Gadus morhua*, concluding that increased CO_2 levels constrained the thermal performance window of embryos. Moreover, a reduction of the thermal tolerances of the sea urchin *Loxechinus albus* and the false abalone *Concholepas concholepas* from Chilean waters was observed as a response to the synergistic effects of ocean warming and acidification (Manríquez et al. 2019, 2020).

Physiological and behavioral responses to climate change will then be evident at the population level as shifts in biomass, phenology (i.e., the timing of recurring life history events), and spatial organization of organisms (Doney et al. 2012). Biomass is affected because the productivity of fish populations, in terms of recruitment, growth, and mortality, is highly influenced by direct and indirect effects of climate change (Rijnsdorp et al. 2009). Under the current climate change scenario, predictions show that marine animal biomass in the South Atlantic will decline between 15% and 30% to 2100 (Bryndum-Buchholz 2019), unless emission mitigation measures are implemented.

Another critical mechanism that allows species to cope with climate change impacts includes altering phenology (Burrows et al. 2011). Marine fish have evolved to align the timing of their seasonal life cycle events with environmental seasonality and other organisms' phenology to maximize survival (Llopiz et al. 2014). Moreover, novel interspecific interactions may occur (i.e., invasive vs. native species), or the strength of preexisting ones may be intensified (i.e., warm- vs. cold-adapted). Under a warming scenario, local or regional relocations following tolerable conditions and reducing competitive costs are viable solutions for mobile species (Parmesan and

Yohe 2003; Parmesan 2006). This process may result in "winner" (warm-adapted) species dominating the best-quality habitat at the expense of the "loser" (cold-adapted) species (Milazzo et al. 2012). An increasing number of studies showed that marine fish geographical ranges are expanding poleward (Perry et al. 2005; Last et al. 2010; Fredston-Hermann et al. 2020) or into deeper depths (Dulvy et al. 2008). Such shifts are generally most evident near the northern or southern boundaries of the geographic range of a species (Pörtner and Peck 2011; Fredston-Hermann et al. 2020). However, these processes' strength will depend on food web complexity, environmental conditions, and interaction with other drivers (Fig. 1), as the direct and indirect effects of climate change on marine ecosystems do not act isolated.

Commercial fishing is another crucial driver that alters the population structure of both targets and incidentally captured organisms and, consequently, the community structure. The direct effects of fishing at the population level include reductions in total biomass and mean body size and, as a result, changes in biomass production. The magnitude of these changes in response to the fishing pressure strongly depends on each species' reproduction and growth features. As a general rule, species exhibiting slow-growing, late-maturing, low fecundity, and long-living are profoundly affected and least resilient to exploitation pressure. All these traits are correlated with maximum body size, and in areas with a history of intensive fishing pressure, fish assemblages have fewer large top predators (Lotze et al. 2011). Previous studies emphasized the simultaneous importance of both fishing (top-down) and climate- (bottom-up)

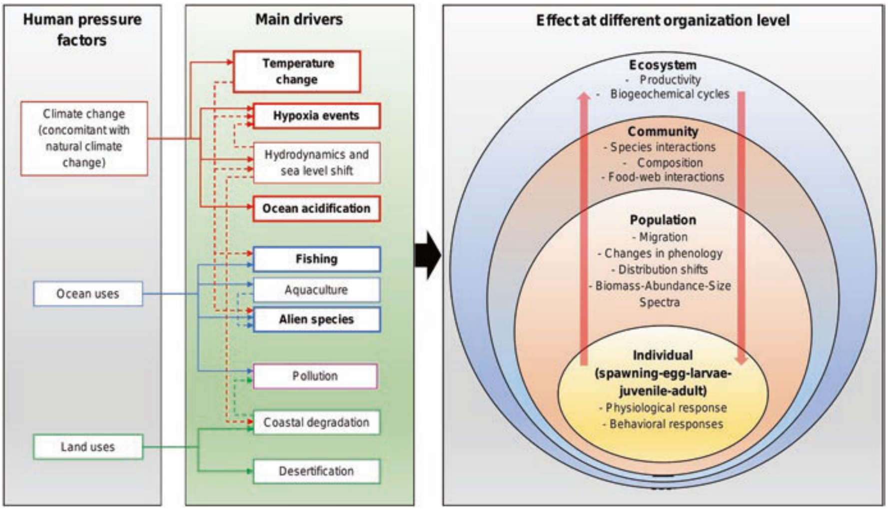

Fig. 1 Conceptual map describing drivers of global change affecting marine fishes. Solid lines denote the connection between human factors and main drivers, and dashed lines represent connections among drivers. The big central connector between main drivers and effects includes both direct and indirect effects. Red lines in the third panel indicate indirect bottom-up and top-down effects. Words in bold and thicker arrows indicate the drivers, connections, and organization levels analyzed in particular for Patagonia throughout this chapter. (Figure adapted from Pörtner and Peck (2011), Rijnsdorp et al. (2009), and Llopiz et al. (2014))

induced effects in marine ecosystem reorganization (Rijnsdorp et al. 2009), with results showing a dichotomous size-dependent response to both drivers (Genner et al. 2010). For instance, in the North sea, it has been shown that small species had rapid responses to the prevailing thermal environment, suggesting that fast-growing and early-maturing populations respond quickly to changing climates (Genner et al. 2010). In contrast, larger species have declined in abundance and size, reflecting expectations from sustained size-selective overharvesting in the area (Genner et al. 2010). In addition to the direct impacts of fishing on fish populations and assemblage structures, there are indirect effects in their functional organization and food web structure. Classic examples of indirect impacts include changes and simplification of food web structures (Frank et al. 2005; Coll et al. 2008; Lotze et al. 2011) and reduction of omnivory (Bascompte et al. 2005) through top-down cascading effects that promote the increase of mesopredators triggered by the overfishing of large predators (Heithaus et al. 2008). Among commercial fisheries, bottom trawling is the dominant gear, responsible for most possible indirect changes in fish community composition and impaired ecosystem functioning (Navia et al. 2012; Amoroso et al. 2018). In some circumstances, and depending on the fish assemblages' composition in the fishing grounds, trawl nets remove many nontarget species, even producing massive discards (e.g., Bovcon et al. 2013). This gear also scraps bottoms, damaging their structural complexity (Martín et al. 2014), and causes changes in the species composition and functional structure of associated benthic invertebrate communities (Tillin et al. 2006; Jimenez et al. 2016; Bolam et al. 2017). Discards and damaged benthic organisms may increase the food supply for scavengers and promote their increase in marine systems (Catchpole et al. 2006). However, intermediate predator fishes can also consume massive food supply, altering their feeding ecology and predator-prey and competitive interactions in a community (Funes et al. 2019). Classic "fishing down the food web" theory indicates that those changes lead to a decrease in the mean trophic level of the fish assemblages (Pauly et al. 1998; Jennings et al. 2002; Pinnegar et al. 2002). However, a review on trophic level changes induced by fishing indicates that effects are case-dependent, and even increases in trophic level may occur (Funes et al. 2019; Funes 2020). Considering that commercial fisheries are increasing the number of species targeted (e.g., Victorero et al. 2018), it is expected that the ecological roles affected increase as well (Trindade-Santos et al. 2020), enhancing the magnitude of indirect mixed effects in ecosystem functioning.

Although climate change and commercial fishing are the main threats to fish diversity, regional pressures also affect coastal areas (Jackson 2008). The intensive use of fertilizers, coastal degradation, increase in aquaculture production, and invasion by alien species are the most harmful (Halpern et al. 2008; Bezerra et al. 2019). Individualizing the effects of all of these drivers acting together is a difficult task that requires independent data collated under specific designs to test singular hypotheses. Given the absence of such data for fish assemblages of the Patagonian coast, in this chapter, we will focus on changes in their diversity due to the combined effects of climate change-related drivers, fishing, and colonization by alien species (Fig. 1). To achieve this goal, we first provided a summary of the published information for Patagonia, and then we reconstructed three coastal fish assemblages and changes in their composition between 1970 and 2020. The approach relies on range shift published records, expert knowledge, and a stage-based model (Bates et al. 2014). The stage-based model assumes that range extensions occur as a sequence of arrival, population increase, and persistence. In contrast, range contractions progress as yield and population decline and local extinctions occur (Bates et al. 2014).

Global Change Effects in the Fish Assemblages Off the Patagonian Coast

Our literature search conducted through the academic web browsers Scopus and Google Scholar returned a low number of references about global change effects on fish assemblages in the Southwest Atlantic (SWA). References were organized and discussed according to the three drivers of global change here analyzed (climate change, fishing, and invasion by alien species) and their individual effects on fish assemblages of Patagonia.

We did not find studies that addressed the climate change's effects on the marine fish assemblages from Patagonia. In the SWA, the first published compilation of gains in range shifts is a technical report for the coastal waters off Buenos Aires province, Argentina (36°S to 38°S). The report collated published and unpublished range expansions toward the south for 34 tropical and subtropical fishes between 2000 and 2017 and related them to an increase of up to 0.5°C in the summer sea surface temperature (SST) during that period (Milessi et al. 2018). Focusing on the relative abundances of the indigenous fishes, rather than on reports of newcomers, Gianelli et al. (2019) and Franco et al. (2020) showed that the mean thermal preference of exploited species weighted by their annual catch increased in Uruguayan landings (34°S–35°S) between the 1980s and 2017, following an increase in the SST.

Although there is extensive literature on the effects of fishing on the populations of commercial species in Patagonia (see Narvarte et al., this volume), few studies focused on analyzing the effects of harvesting on the structure and composition of fish assemblages. These studies come mostly from northern and central Patagonia. In San Matías gulf (northern Patagonia), the industrial bottom trawl and the small longline artisanal fleet that operates in the area seem to have replaced several predators over the food web, even a previously depleted population of the South American sea lion *Otaria flavescens* that prey over hake and other species (Ocampo Reinaldo et al. 2016). Those fisheries mainly target the Argentine hake *Merluccius hubbsi* but affect 32 cartilaginous and 45 bony fishes and have shown increasing trawling discards rates over the years (Romero et al. 2010). The landing composition and the spatial distribution of the fishing effort of the industrial fleet are mostly related to the environmental-driven fish distribution and temporary market opportunities for new target species (e.g., silver warehou *Seriolella porosa* or Patagonian shrimp *Pleoticus muelleri*; Ocampo Reinaldo et al. 2013; Romero et al. 2013). In central Patagonia, the shrimp trawl fleet, one of the most important fisheries in the area, caught 101 incidental species comprised of three jawless fishes (agnatha), 29 cartilaginous, and 69 bony fishes (Góngora 2011; Ruibal

Nuñez 2020; Góngora et al. 2020). Based on the life history, abundance, and conservation status of the bycatch species, nine were identified as potentially threatened by the shrimp fishery and 31 as not impacted due to their low frequency in the catch. The level of impact caused by the incidental capture of the remaining species is unknown (Góngora 2011). The same fish assemblage also had evidence of a decrease in the proportional biomass of cartilaginous to bony fishes that correlated positively with the shrimp trawl fleet's fishing effort between 1998 and 2018 (Funes 2020). These studies identified threats and some changes in the fish assemblages structure caused by incidental fishing of the shrimp fleet in Patagonia; however, the effects of other fisheries in the area are still unknown.

The Patagonian marine region does not escape from species introductions and invasions. A total of 63 introduced species belonging to different taxa, from 129 reported in the SWA, have appeared in Patagonian waters (Schwindt et al. 2020). The salmonids *Salmo trutta*, *Oncorhynchus mykiss*, *Oncorhynchus tshawytscha*, and *Oncorhynchus kisutch* are the four alien fishes identified in Patagonia (Chalde et al. 2019; Figueroa 2019; Schwindt et al. 2020). A century ago, *S. trutta* and *O. mykiss* were introduced in rivers and lakes of Patagonia, and later they established anadromous populations (Pascual and Ciancio 2007). Escapements of salmon ranching in Chile facilitated the invasion of *O. tshawytscha* and *O. kisutch*, which actively colonized the Argentinean marine waters (Ciancio et al. 2005; Chalde et al. 2019). The evaluation of these salmonids' potential impact on their prey showed that it would be negligible for the populations of *Sprattus fuegensis*, but instead, they could cause depletions in the abundance of *Odontesthes smitti* (Ciancio et al. 2010).

Reconstruction of Fish Assemblages Off the Patagonian Coast

To evaluate patterns of change properly, a baseline of information on species occurrence is a primary condition to be accomplished (e.g., Lotze et al. (2006), Bates et al. (2014)). Despite the good understanding of the Argentinean waters biogeography (see Box 1), detailed lists of alien species (Schwindt et al. 2020), and reports on fish range expansions and rare occurrences (see references in the appendix ESM 1), we did not identify previously comprehensive lists of the coastal fish assemblages' composition of Patagonia to test distribution change patterns. For this review, we first compiled species checklists for three coastal areas (gulfs and continental shelf up to 100 m in depth) representative of the northern (40°S–42°S, San Matías gulf), central (43°S–47°S), and southern Patagonia (50°S–55°S) (Fig. 2). Then, we classified fishes according to their occurrence history, biogeographical origin, fishery relevance, and thermal preference. And we examined the resulting database in the search of trends, and we postulated correlations with drivers of global change. Also, we suggested future research lines aimed to evaluate how these changes in the composition of the assemblages might impact ecosystem function and structure.

We selected an area-based approach because of its representativeness of a zoogeographical condition and data availability to achieve a good reconstruction of the

Box 1 Biogeographic Context

Two biogeographic provinces characterize the main distribution patterns of marine fishes in the southern region of the Southwest Atlantic ocean (SWA): the Magellanic and the Argentine provinces (Balech 1954; López 1963, 1964; Balech and Ehrlich 2008). The Argentinean province (Fig. 2) extends over the continental shelf from a northern limit that fluctuates between 30°S and 32°S (Rio Grande do Sul, Brazil) to a southern boundary in northern Patagonia between 41°S and 44°S (Balech and Ehrlich 2008). The Argentine province comprises the South Brazilian and Bonaerense districts (Fig. 2) located to the north and the south of the 34°S latitude, respectively (Menni et al. 1981; Menni and Stehmann 2000). The Magellanic province includes the Patagonian shelf from Valdés peninsula (43°S) to Cabo de Hornos (55°S), and it follows a northward path along the edge of the continental shelf (Balech and Ehrlich 2008; Cousseau et al. 2020). This province splits into the South Chilean district in the Pacific ocean and the Patagonian district in the Atlantic (Menni and Stehmann 2000). The biogeographic differences between the two provinces are mainly associated with lower water temperatures of sub-Antarctic origin in the Magellanic province and higher water temperatures with a subtropical origin in the Argentine province (Menni and Stehmann 2000).

The ichthyofauna of these two large provinces is well-documented and consistent for both chondrichthyans and teleosts, and their species lists are based mainly on data from surveys carried out by foreign and national scientific expeditions carried out up to 1990 (Norman 1937; Krefft 1968; Menni 1981; Menni and Gosztonyi 1982; Menni and López 1984; Menni and Stehmann 2000; Menni et al. 2010). Menni and Gosztonyi (1982) demonstrated the spatial and temporal stability in the species composition of fish assemblages in the Argentine sea during 10 years using data from the Kaiyo Maru survey carried out between 1969 and 1970 and from the Orient Maru I survey, carried out between October 1976 and January 1977. Then, Menni and López (1984) recognized the same defined assemblages using data from the Shinkai Maru survey collated in 1978. However, the biogeographic scheme proposed between the 1960s and the 1980s changed since the 1990s, with accentuation in the 2000s, due to temperate-warm fishes from the Argentine province and subtropical species that moved southward to central Patagonia (47°S). Some indicators for these changes include the finding of reproductive populations of sciaenids (*Micropogonias furnieri*, *Cynoscion guatucupa*) and sparids (*Diplodus argenteus*, *Pagrus pagrus*), typical of the Argentine province, in waters belonging to the Magellanic province (Galván et al. 2005; Góngora et al. 2009; Bovcon et al. 2011).

assemblages and their potential changes. The availability of data on the occurrence of coastal fishes was related to the historical settlement of academic and scientific institutions (Fig. 2) and the existence of regular on-board observer programs carried out by the fishery authorities of Río Negro and Chubut (e.g., Bovcon et al. (2011), Romero et al. (2013)). Although the areas chosen have different sizes, relative comparisons of the observed changes in each area can be made. The northern area, the San Matías gulf, is a semi-closed basin with a limited water exchange with the adjacent shelf. The gulf has two depressions of 160 and 216 m in depth, one located to the south and the other to the north of the parallel 41°40'S. Primary and secondary productions seem sustained by at least three areas: a tidal front, which extends in a

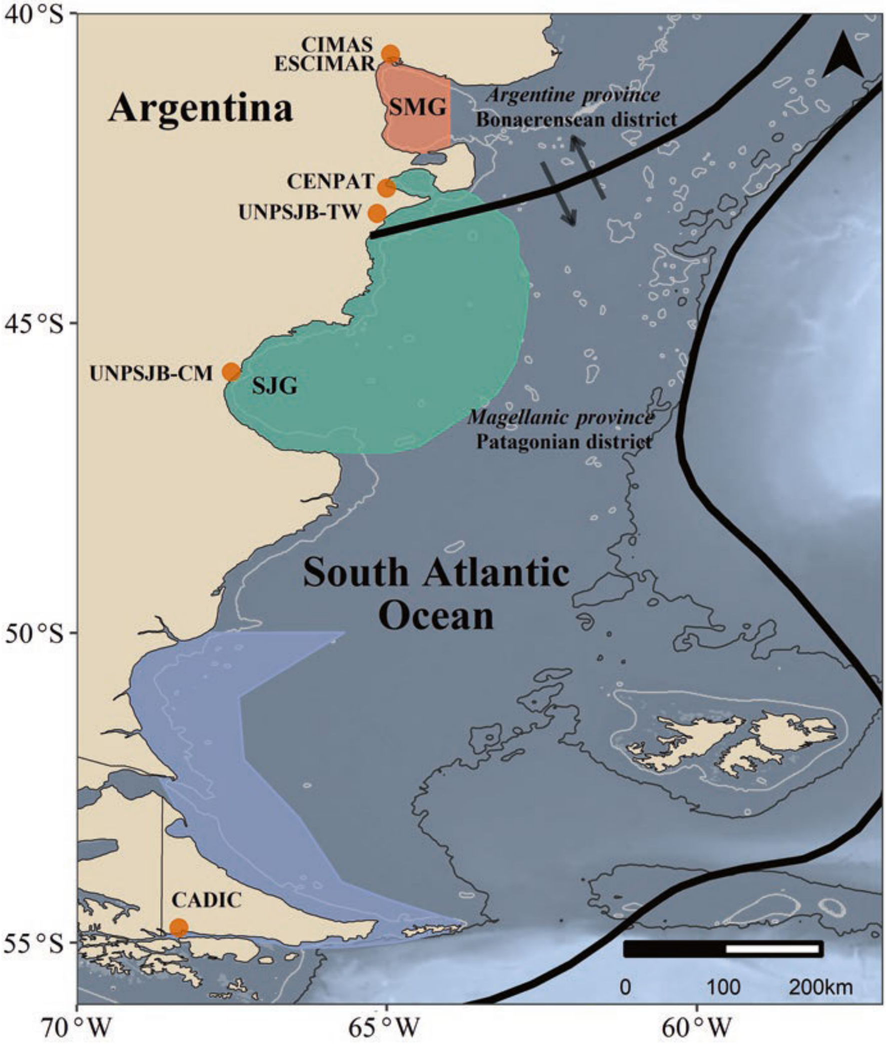

Fig. 2 Study areas, location of historical research institutes (orange dots), and biogeographical provinces in Argentine Patagonia. The location of biogeographical provinces follows the scheme by Balech and Ehrlich (2008). CIMAS: Centro de Investigación Aplicada y Transferencia Tecnológica en Recursos Marinos Almirante Storni; ESCIMAR: Escuela Superior de Ciencias Marinas (University of Comahue); CENPAT: Centro Nacional Patagónico; UNPSJB: Universidad Nacional de la Patagonia San Juan Bosco; TW: Trelew; CM: Comodoro Rivadavia; CADIC: Centro Austral de Investigaciones Científicas; SMG: San Matías gulf and SJG: San Jorge gulf

northwest-southwest direction from October to March, the San Antonio bay in the North and the San José gulf in the South (Svendsen et al. 2020). The central Patagonia area encompasses the San Jorge gulf and adjacent northern waters up to 100 meters in depth. The gulf is a shallow basin with the deepest area around 100 m in depth in its center and a bank at its eastern limit (60 to 90 m in depth) (Matano and Palma 2018). Production in the area is supported by two fronts in the San Jorge gulf (a southern thermohaline front and a northern tidal front) and the Valdés tidal front extending to northern shelf waters (Bogazzi et al. 2005). The southern Patagonia area encompasses the continental shelf up to 100 m in depth between 50°S and 55°S. Primary and secondary production are supported mainly by the Atlantic Patagonia cold estuarine front, close to the Pacific Patagonia cold estuarine front (Acha et al. 2004). In the Beagle channel sector, there is evidence of significant energy input of terrestrial detritus (Riccialdelli et al. 2017). For more details on the oceanography of the Patagonian continental shelf, see chapters by Saraceno et al. and Villafañe et al., this volume.

The reconstruction of the fish assemblages involved an extensive review of records encompassing the period 1970–2020. Sources of data included published papers and books; unpublished theses; databases from local ichthyological collections; technical reports from exploratory fishing surveys that partially covered the areas of interest; records from the provincial observer programs that monitor commercial fisheries; landing statistics from commercial, artisanal, and recreational fisheries; and personal observations provided by authors of this chapter (ESM 1).

We classified species occurrences, status (*sensu* Evans et al. 2020), and temporal distributional trends within each selected area for the compiled species records, following the categories proposed in Table 1.

To assess the robustness of our reconstructions, we also evaluated the information quality. A score of information quality ranging between 1 and 4 was assigned to each species based on an *ad hoc* criteria (e.g., Bates et al. (2014)): (1) general knowledge but uncheckable, (2) unpublished personal observations made by the authors of this chapter, (3) published personal observations, and (4) certified data in which the authors captured individuals or studied captured material (e.g., peer-reviewed papers, reports, and museum collections).

Coastal Fish Assemblages of Northern, Central, and Southern Patagonia

According to the latest update on fish diversity of the Argentine sea (Figueroa 2019), 601 fish species have been recorded. For the three areas considered in this chapter, we collated records of occurrence for 192 species between the years 1970 and 2020 (Table 2 and Fig. 3). Those species belong to 5 classes and 86 families. The three reconstructed assemblages comprised 35% of the Argentine ichthyofauna and showed a decreasing gradient in richness toward higher latitudes. This pattern is consistent with the expected latitudinal trends in overall fish species richness (Macpherson 2002) and studies on particular groups, such as rocky reef fishes in the

Table 1 Categories used for classifying species occurrences, status, and temporal distributional trends within each study area

Major trait	Category	Definition
Species occurrence	Anecdotic	Fishes recorded only once in the area
	Occasional	Fishes recorded more than once in the area, but their presence is considered rare
	Resident	Fishes present in the area throughout the year
	Seasonal	Fishes present in the area only during part of the year
Status (*sensu* Evans et al. 2020)	Indigenous	Fishes with their historic native range within the area
	Alien	Human-introduced fishes that survive in a new area, expanding their historical range
	Range shift gain	Fishes that expanded their distributional ranges and established populations in a new area without human intervention
	Vagrant	Fishes that arrived as isolated cases by natural dispersal from a neighboring area without human intervention
	Cryptogenic	Fishes with an origin that cannot be cataloged as native, vagrant, range-expanding, or introduced
	Range shift loss	Fishes that showed retractions in their distributional ranges
Trends in fish distribution	Expansion	Fishes that appeared for the first time in an area
	Partial expansion	Fishes whose observed frequency or abundance increased in an area
	Retraction	Fishes that disappeared from an area due to local extinction processes
	Partial retraction	Fishes whose observed frequency or abundance decreased in an area
	No change	Fishes whose observed frequency or abundance maintained relatively constant in an area
	Insufficient data	Lack of or uncheckable data

SWA (Floeter et al. 2004; Galván et al. 2009) or chondrichthyans (Lucifora et al. 2012; Sabadin et al. 2020).

The reconstructions of fish species occurrence and their status in the studied assemblages are robust because they relied primarily on certified scientific data; the numbers of species with an information quality score equal to 4 were 106 (96.3%) in northern Patagonia, 138 (96.5%) in central Patagonia, and 83 (97.6%) in southern Patagonia (see ESM 1 for details). On the other hand, trends in fish distribution have a majority of species classified as data deficiency. The number of species with insufficient data were 56 (51.4%) in northern Patagonia, 57 (39.9%) in central Patagonia, and 61 (71.8%) in southern Patagonia (Fig. 3).

Table 2 Number of species and families (between brackets), by class, collated for the three assemblages and Argentina. The numbers for Argentina were extracted from Figueroa (2019)

Class	Northern Patagonia	Central Patagonia	Southern Patagonia	Argentina
Myxini	–	2 (1)	1(1)	7(1)
Cephalaspidomorphi	1 (1)	1 (1)	1 (1)	1 (1)
Holocephali	1 (1)	1 (1)	1 (1)	2 (2)
Elasmobranchii	34 (16)	33 (14)	17 (5)	110 (24)
Actinopterygii	75 (48)	106 (54)	65 (33)	481(154)
Total	111 (65)	143 (71)	85 (41)	601 (182)

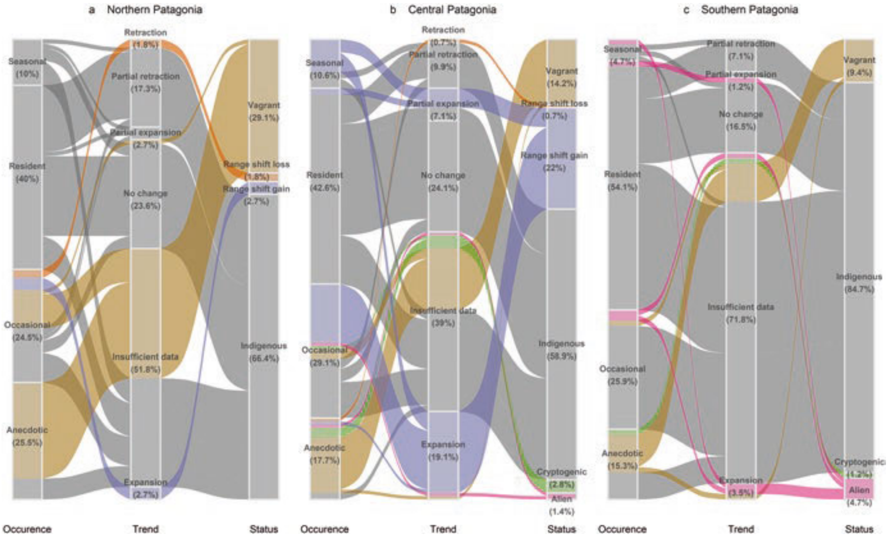

Fig. 3 Relationships among the categories of species' occurrence, distribution trend (range shift stage), and distribution status (Evans et al. 2020) for each study area. Categorical classifications for occurrence, trend, and status were divided into blocks in each column. Blocks sizes represent the proportion of species for each level, and stream fields between the alluvial diagrams' blocks represent the proportion of species corresponding to each level through all categories. The stream fields are color coded according to the distribution status category. Names of levels for each category and their proportion (percentages in brackets) are located in the middle of the corresponding blocks

Fish Diversity Gains and Range Expansions

Overall, 30 species showed records beyond their indigenous distributional ranges during the time-window analyzed (ESM1). Among these, 27 cases were gains due to range expansions, and three were alien species (Fig. 3). Broken down by area, central Patagonia exhibited more gains, in total and relative numbers, than the other two regions (Fig. 3). Around 18% of the species identified for that area correspond to newcomers, against around 3% for northern and southern Patagonia. As previously described, the central area encompasses the confluence between the Argentine and the Magellanic provinces, which makes it an excellent site to detect changes in species distribution driven by temperature or oceanographic conditions. A biogeographical analysis of the newcomers to the central area showed that the changes mainly consisted of the arrival of species expanding from the north (Table 3 and ESM 2). The mean thermal preference of the species that expanded their distributional range was higher than the mean thermal preference of the species that previously occurred in the area (Fig. 4). Both variables, thermal preference and biogeographical origin, were highly correlated and suggested a process of tropicalization in the area (i.e., an increase in tropical species dominance in temperate assemblages, *sensu* Cheung et al. (2009, 2012)). In the northern area, the three newcomers (100% of gains) were from warmer regions (*Epinephelus marginatus*, *Genidens barbus*, and *Symphurus plagusia*, Table 3, ESM 2). In the central area, 86% of newcomers were from warmer areas; 7% were alien species (*O. mykiss* and *S. trutta*), and 7% were species from cold waters (*Mendosoma lineatum* and *Paranotothenia magellanica*) (Table 2). The latter seems to be expanding to the North since it was occasionally recorded in coastal waters off Mar del Plata and Necochea, in Buenos Aires province, at 38°S (Figueroa et al. 2005; Venerus pers. com.). The complete list of newcomers from warmer waters to the central area includes *Atlantoraja castelnaui*, *Atlantoraja cyclophora*, *Atlantoraja platana*, *Conger orbignianus*, *Epinephelus marginatus*, *Genidens barbus*, *Genidens planifrons*, *Hyporthodus niveatus*, *Maurolicus stehmanni*, *Micropogonias furnieri*, *Mullus argentinae*, *Myliobatis ridens*, *Pagrus pagrus*, *Prionotus nudigula*, *Psammobatis bergi*, *Selene setapinnis*, *Seriola lalandi*, *Tetronarce puelcha*, *Thyrsitops lepidopoides*, *Trachurus lathami*, *Trichiurus lepturus*, *Urophycis brasiliensis*, and *Zenopsis conchifer*. In the southern area, the alien species *O. tshawytscha* and *O. kisutch*, in addition to the salmonids mentioned for central Patagonia, represented all the changes recorded in the assemblage composition (Table 3). It is remarkable that the white sea catfish *G. barbus* was identified as a newcomer in the three study areas and that the dusky grouper *E. marginatus* was identified as a newcomer in the northern and central areas, and both species come from warm-temperate waters.

Among the indigenous species in each assemblage, we detected several cases of fishes whose observation frequency increased. Again, our data showed that central Patagonia exhibited more increases in total and relative numbers among the evaluated areas. In the northern area, the three species that increased in abundance, *C. guatucupa*, *D. argenteus*, and *P. pagrus*, are all common species from warm-temperate and tropical areas. Even the last two species expanded their ranges into the central area. A total of nine species increased their frequency of occurrence in the central area. From them, eight had warm-temperate distribution (*Scomber colias*, *Psammobatis extenta*, *Oncopterus darwinii, D. argenteus*, *Dules auriga*, *Symterygia acuta*, *Squatina guggenheim*, and *Paralichthys patagonicus*), while one (*Cottoperca trigloides*) occurs in cold-temperate waters. The only species for which a partial increase was detected in

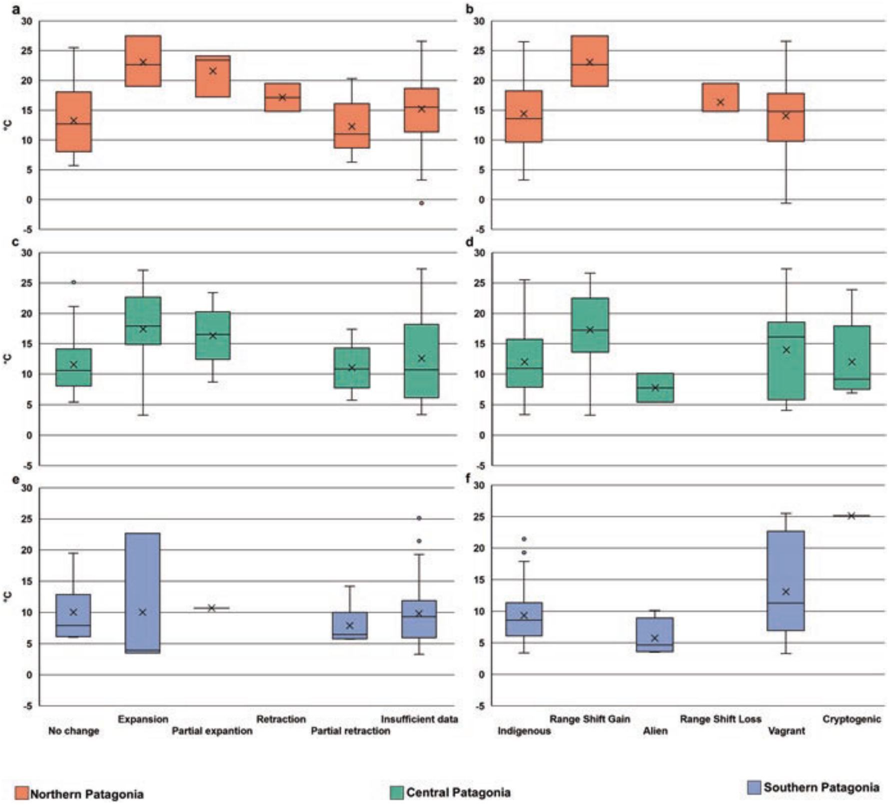

Fig. 4 Mean temperature preferences for fishes in the three study areas by categories of temporal trends (**a**, **c**, and **e**) and status (**b**, **d**, and **f**). Temperature data were obtained from FishBase (Froese and Pauly 2019). The boxes comprise the 25th and 75th percentiles for the sample. Whiskers extend between the minimum and maximum values within 1.5 times the box ranges. The horizontal lines within the boxes show the median, x markers represent the mean values, and the dots indicate outliers

the southern Patagonian assemblage was *Eleginops maclovinus*, an endemic fish of the Magellanic province (occurring at both Atlantic and Pacific coasts) and typical of central Patagonia. However, *E. maclovinus* has also been recorded in northern waters, in the coastal lagoon of Mar Chiquita, 37°40'S (Gonzalez Castro et al. 2013), and it seems to be expanding toward the North.

Fish Diversity Losses and Range Retractions

The only two species that have fully retreated are elasmobranchs. Both *Rioraja agassizii* and *S. acuta* occurred in the northern area, and their distributions extend to warmer waters. There were no species identified as losses at central and south Patagonia. We identified a total of 30 species in partial retraction. Species exhibiting

Table 3 Biogeographical origin of the species listed in each study area. The numbers of species expanding their distributional ranges are informed between brackets. The biogeographical origin follows the classification proposed by Figueroa (2019). Numbers in bold letters highlight the expansions

	Biogeography	Northern Patagonia	Central Patagonia	Southern Patagonia
Warm waters	Circumtropical	**21 (1)**	**21 (10)**	1
	Brazilian	**5 (1)**	**4 (1)**	0
	Argentine	**41 (1)**	**43 (13)**	**6 (1)**
Cold waters	Magellanic	25	**40 (1)**	52
	Circum-antitropical	5	9	5
	Antarctic	0	2	4
	Southern Hemisphere	9	**21 (1)**	13
Alien		0	**2 (2)**	**4 (2)**

total or partial retraction did not show a different thermal preference from the species identified as no changing (Fig. 4a, c, e). Seventy-five percent of the species whose observed frequency or abundance decreased are targeted by commercial or recreational fisheries. The species in retraction decreased both in raw and relative numbers from north to south (Fig. 3). At northern Patagonia, 19 species (17%) were identified as in partial retraction, five of which were elasmobranchs (*Galeorhinus galeus*, *Mustelus schmitti*, *Psammobatis bergi*, *Squalus acanthias*, and *S. guggenheim*), and 14 were teleosts (*Acanthistius patachonicus*, *Congiopodus peruvianus*, *Genypterus brasiliensis*, *M. argentinae*, *Nemadactylus bergi*, *Paralichthys isosceles*, *Parona signata*, *Percophis brasiliensis*, *Polyprion americanus*, *P. nudigula*, *Pseudopercis semifasciata*, *Seriolella porosa*, *Stromateus brasiliensis*, and *Xystreurys rasile*). Thirteen of those species have a commercial interest, and five are also caught by recreational fishers (Fig. 5). In central Patagonia, 14 species (10%) were identified as in partial retraction, 5 were elasmobranchs (*S. acanthias*, *Carcharhinus brachyurus*, *M. schmitti*, *G. galeus*, and *Notorynchus cepedianus*), and 9 were teleosts (*A. patachonicus*, *P. americanus*, *P. semifasciata*, *P. brasilianus*, *Brama brama*, *Genypterus blacodes*, *Macruronus magellanicus*, *Salilota australis*, and *Hippocampus patagonicus*). Five of those species are harvested by commercial and recreational fisheries, two have only a commercial interest, and three are targeted exclusively by the recreational sector (Fig. 5). In northern and central Patagonia, there are well-established onboard observer programs maintained by provincial governments that allowed the reconstruction of the three assemblages and better assignment of the qualitative trends for both targeted and incidentally captured species (Caille et al. 1997; Bovcon et al. 2013; Romero et al. 2013; Góngora et al. 2020). Unfortunately, there is no such detailed information available for the southern assemblage. Therefore, the number of species classified as data insufficient in the southern area was higher than for the other two areas, and the species in the other categories were biased toward those commercially targeted. At southern Patagonia, we identified six species (7%) in partial retraction; one shark

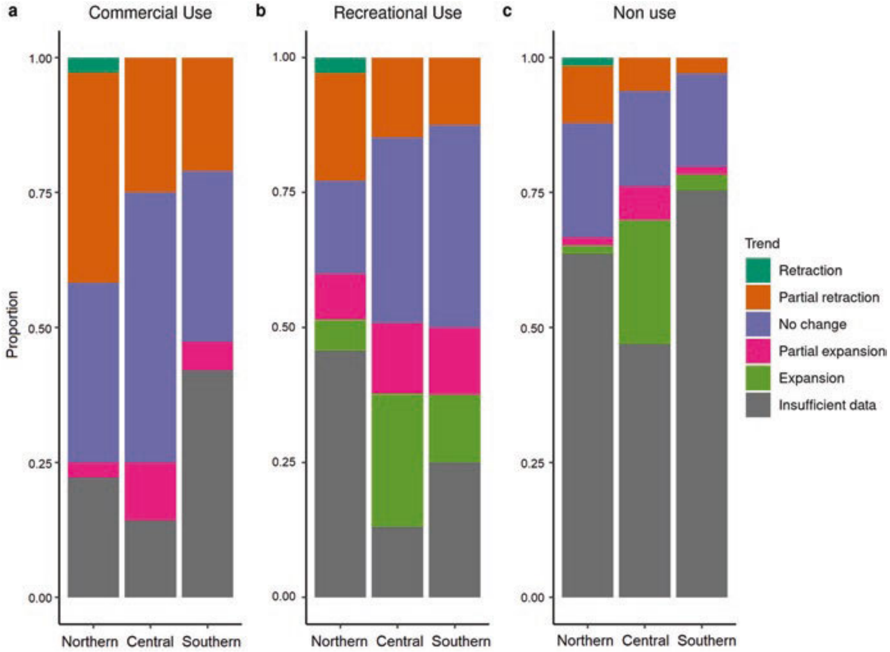

Fig. 5 Proportions of species classified by use and temporal trends in the studied areas. Commercial use comprises the landings of industrial and artisanal fisheries. Recreational use covers species targeted by sport anglers and spearfishers. Recreational and commercial use are not mutually exclusive categories. Non use comprises the rest of the species

captured by recreational anglers (*N. cepedianus*) and five teleosts (*M. magellanicus*, *Merluccius australis*, *Micromesistius australis*, *S. australis*, and *Champsocephalus esox*). The first four of those fishes represent important commercial resources. We identified seven species with partial retractions in two study areas commonly caught by trawling fleets: *A. patachonicus*, *G. galeus*, *M. schmitti*, *P. semifasciata*, and *S. acanthias* in the northern and central areas and *M. magellanicus* and *N. cepedianus* in the central and southern areas. This finding may suggest a population decrease exceeding the Patagonian region, probably due to overfishing.

Drivers of Gains and Losses in Fish Biodiversity and Resulting Assemblage Patterns

The observed changes in distributional ranges of fish species documented in this chapter show that, as in other temperate locations where water temperature has increased, species gains outpaced losses (Antao et al. 2020). Then, the observed trend in Patagonia is consistent with the expectation of an increase in local marine richness, as temperate regions undergoing warming will receive an influx of species following suitable temperatures and increases in the occurrence of warm-affinity generalists, indigenous from those regions (Burrows et al. 2019; Antao et al. 2020). As mentioned earlier in this chapter, these spatial shifts are part of a global biogeographic pattern of change known as tropicalization (Cheung et al. 2009, 2012). Fishes may be expanding their distribution ranges following the warming of temperate waters, but they may also be leaving northern regions to avoid temperatures higher than their physiological tolerance because those regions are experiencing high warming (Franco et al. 2020). At a regional scale, the tropicalization of temperate seas produces a rapid biotic homogenization of the fish assemblages (i.e., the species identity of colder localities increasingly resembled that of warmer localities; Magurran et al. (2015); Bezerra et al. (2019)). In Patagonia, the arrival of fish from warmer localities increased the similarity in species composition between the northern and the central areas by 8% and between the northern and the southern areas by 1% (these percentages are the differences between Jaccard similarity indexes with and without newcomers). This slight trend may suggest that homogenization of coastal fish assemblages in Patagonia already started.

Several pieces of evidence point to the occurrence of a warming process in the SWA. Southern Brazil, Uruguay, and the northern Patagonian shelf of Argentina are climate hotspots (i.e., regions where the SST has changed most rapidly in the last 50 years, and it is expected to increase more than 3°C by 2099; Popova et al. (2016)). Since the 1980s, the position of the 20°C and 17°C isotherms showed a constant long-term displacement toward the poles (Ortega et al. 2016; Gianelli et al. 2019). The data presented and discussed by Saraceno et al. (this volume) showed that the SST in Patagonia increased to the north of 48°S but diminished southward. The observed influx of species from warmer waters to the northern and central, but not to the southern area described in this chapter, follows the spatial changes in SST observed for the Patagonian region and suggests that fishes are good early indicators of regional warming, as it was proposed by Fogarty et al. (2017). In agreement with the general spatial pattern described for Patagonian fishes, a recent biodiversity analysis on macroinvertebrate assemblages showed the first symptoms of tropicalization in the San Jorge gulf due to southward range extensions of warm-temperate species in the area (see López Gappa this volume).

Even though tropicalization has been evidenced in the ichthyofauna of Patagonia, the dispersion of two species of the suborder Notothenioidei, *P. magellanica* and *E. maclovinus*, toward lower latitudes, should be highlighted. Both species are typical representatives of the Magellanic province and were recently observed in the province of Buenos Aires, Argentina (Figueroa et al. 2005; González-Castro et al. 2013). Notothenids were suggested as a group in expansion toward temperate waters, a process explained by their origin in moderately warm shallow seas that connected Australia, Antarctica, and South America within the province of Weddell, which existed from the Upper Cretaceous to the Eocene (Balushkin 2000). In fact, *E. maclovinus* is distributed in environments that are widely cooler than their maximum thermal tolerance and preferred temperature range (Lattuca et al. 2018). Therefore, *E. maclovinus* would be expected to be influenced in its current distribution by indirect effects of climate change, such as habitat degradation or changes in trophic structure, rather than by direct effects (Fig. 1) (Lattuca et al. 2018).

We observed a decrease in the ratio of elasmobranchs to teleosts from north to south in the three assemblages. The ratio was 31% in the northern area, 23% in the central, and 20% in the southern area. This finding follows the general pattern described for chondrichthyans in the SWA (Lucifora et al. 2012), which showed the highest richness of elasmobranchs at the continental shelf off Uruguay and southern Brazil, with another small peak at El Rincón, 39°S (Sabadin et al. 2020). Under the current results, a proportional increase of elasmobranchs would be expected if there were an influx of species from the north, and both elasmobranchs and teleosts had similar chances of extending their ranges. However, elasmobranchs were proportionally more affected by total or partial losses than gains when the three assemblages were analyzed together. This trend is consistent with the expectation that, as elasmobranchs are slow-growing and late-maturing species, they respond slowly to climate change (Genner et al. 2010) and are more prone to decline by the direct effects of fishing or the cascading indirect effects of global change (Dulvy et al. 2014). In central Patagonia, 26 of the 34 registered cartilaginous fishes are caught incidentally by the commercial fisheries that target hake and shrimp and are also discarded on board or landed as byproducts (Góngora et al. 2009, 2020; Cedrola et al. 2012; Bovcon et al. 2013; Ruibal Nuñez et al. 2016, 2020). In agreement with our results, Funes (2020) reported a decrease in the proportional biomass of elasmobranchs to teleosts and a decrease in the maximum fish sizes observed at the San Jorge gulf (central Patagonia), analyzing independent fishery data from 1998 to 2018. These two trends described in central Patagonia are the most anticipated ecosystem alterations caused by the long-lived species' sensitivity and high catchability by trawling (Reynolds et al. 2001).

General Conclusions and Future Research Perspectives

Understanding the temporal stability of fish assemblage's composition under changing marine environments is crucial to identify drivers and trajectories of ecosystem function and productivity in marine systems. This stage requires an outstanding effort to compile historical occurrences of fish species at regional levels and evaluate the quality of this evidence (Bates et al. 2014). Our study represents the first approach to reconstruct the species composition of fish assemblages located in three well-studied and productive areas along the Argentine Patagonian continental shelf. We discuss our findings as direct effects of three main drivers, climate change, fishing, and invasion by alien fishes. However, other drivers like pollution or other causes of environmental alteration may also affect fishes (Fig. 1, Bezerra et al. (2019)). Besides the direct effects of various drivers, there are also indirect effects (Fig. 1). For example, the environmental alteration of the shallow bottoms caused by the invasion of the annual kelp *Undaria pinnatifida* has antagonist results in the reef fish fauna of Patagonia. On the one hand, it blocks the access to shelter, crevices, and holes used by reef fishes, having a negative effect (Irigoyen et al. 2011a), but also it increases the abundance of their prey, promoting a positive bottom-up effect (Irigoyen et al. 2011b). Future research should then make efforts to incorporate more drivers than those discussed here and their possible synergies and antagonisms.

We found important information gaps in the trends for the geographic distribution ranges of fishes among the three evaluated areas. More than 40% of the species had insufficient occurrence and abundance data to detect changes in their geographic distributional ranges. This fact represents an information gap in the basic ecological knowledge of marine fish species in the Patagonian region. We hope that other researchers might benefit from our information quality list for the occurrence of fish species (see ESM 1) and make efforts to monitor the abundance of fishes with low information quality, such as vagrant species with anecdotal occurrences or non-commercial fishes in coastal areas (Fig. 3). Monitoring the abundance of fish species with gaps and low-quality information in trends of distributional ranges would hamper a reliable identification of climatic and anthropogenic drivers of change of the taxonomic composition, functional organization, and productivity of fish communities in the Argentine Patagonian sea.

Changes in the geographic distributional range of fish species presented in this chapter also constitute a baseline to predict the chances that species have to settle and colonize new areas in the Patagonian marine region. Distributional range shifts in marine fishes correlate with functional traits of morphological (e.g., body size), behavioral (e.g., feeding mode, microhabitat selection), life history (rate of growth), and physiological type (e.g., thermal tolerance) (e.g., Sunday et al. 2015). Such traits determine the species' resistance and adaptability to changing environmental conditions and disturbances (Sunday et al. 2015). As a result, functional traits might facilitate predictions on species composition in novel communities from a functional biodiversity perspective. For example, fish species that have effectively colonized warming areas in the temperate northern Atlantic ocean exhibit high physiological plasticity to colder waters poleward (Dulvy et al. 2008; Wood et al. 2019; Fredston-Hermann et al. 2020) or warmer waters in the Mediterranean region (Moullect et al. 2019). Many vagrant fishes have broad latitudinal geographic ranges that allow greater environmental adaptability, resource use, and successful colonization in new regions (Frainer et al. 2017). Alternatively, functional traits such as body size and maturity age of marine fishes may account for distributional range shifts caused by the synergy between high fishing intensity and climate change. While highly fished communities shift from the large body size and late maturity fish species with commercial importance toward communities dominated by smaller body size and more fecund species (Barausse et al. 2011), other communities located in areas with low fishing pressure and colder waters shift by the influx of large species with commercial interest from lower latitudes (Wiedmann et al. 2014). Identifying the functional traits that correlate with species gains and losses is crucial to understanding ecosystem functioning changes and predicting possible indirect effects in food web functioning and community structure.

Few studies have used a functional trait approach to describe the distribution range shifts in marine fish species in the southern ocean. Existing works mainly focus on describing the thermal responses and tolerance (Lattuca et al. 2018), morphological modifications caused by heat stress (Garofalo et al. 2019), and blood-freezing levels in specific groups of Antarctic fishes (Bilyk 2011). However, studies at the community level in the Patagonian continental shelf remain pending in the regional research agenda. Therefore, future work should aim to create databases of functional traits potentially relevant to explain distributional range changes in marine fishes and evaluate those traits as indicators to predict future scenarios of the functional organization of fish communities in the Patagonian region. Collaborative efforts among researchers working in the region are needed to achieve this goal, whose information is a priority for proposals on biodiversity conservation and fisheries' adaptive management in changing ecosystems.

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Long-Term Ecology Studies in Patagonian Seabirds: A Review with the Imperial Cormorant as a Case Study

Flavio Quintana, Rory Wilson, Nicolás Prandoni, Walter S. Svagelj, and Agustina Gómez-Laich

Global Change and Seabirds

As it has been mentioned in different chapters of this book, it is now widely accepted that global change, and particularly climate variability, has strong and persistent effects on marine ecosystems (Harley et al. 2006; Hoegh-Guldberg and Bruno 2010). In addition to climate change, marine environments (i.e., food webs, biological diversity, and others) are also changing rapidly across the globe for a suite of reasons, some of them as a consequence of anthropogenic activities, including pollution (via heavy metals, organochlorides, oil products, and plastics), coastal development, resource use, energy, transport, overfishing, etc. (Halpern et al. 2008; Poloczanska et al. 2013). These effects have altered the phytoplankton-zooplankton

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ecosystems, thus changing bottom-up processes throughout the pelagic food chain (Richardson and Schoeman 2004; Hays et al. 2005) with consequences for mid-trophic level fish which are the principal prey for several marine top predators (Cury et al. 2000; Frederiksen et al. 2006).

All mentioned natural and human-induced changes are worldwide and recurrent threats to seabirds and have both direct and indirect impacts on this group (see review in Schreiber and Burger 2002). In addition to climate change (and others mentioned above), threats to seabird populations also include habitat loss and degradation due to invasive species, coastal development, physiological stressors due to food shortages and pollution, and mortality due to bycatch in certain types of fishing (Lewison et al. 2012). Particularly, the effects of climatic factors on seabirds appear to be mostly indirect, mainly affecting the local to regional food webs and the pelagic habitat. Seabirds mainly prey upon fish, squids, copepods, and krill that appear to be more sensitive to climatic variations than upper-trophic-level species (Richardson 2008; Sydeman et al. 2012). However, changes in the distribution and abundance of prey are presumed to have direct effects on seabirds through changes in bottom-up food web dynamics (Ware and Thomson 2005) and predator-prey interactions. Despite that, it is clear that climate variability and change influence seabird reproduction, distribution, phenology, and survival in many regions of the globe, both on large and local scales (Barbraud and Weimerskirch 2006; Jenouvrier et al. 2018). In birds, the timing of breeding has been hypothesized to be the reproductive parameter most influenced by climate change (Przybylo et al. 2000). However, studies of seabird breeding phenology have reported a variety of trends over time (Chambers et al. 2014), and the current evidence (see Keogan et al. 2018) indicates that the phenology of species occupying higher trophic levels is less responsive to environmental change than that of primary producers and consumers (Visser et al. 2004; Thackeray et al. 2016), making them particularly susceptible to trophic mismatch and the associated negative demographic consequences (Thackeray et al. 2010; Poloczanska et al. 2013). Previous studies that have combined estimates of phenological change over time or in response to temperature, of multiple high-trophic-level species to global change (Thackeray et al. 2010, 2016; Sydeman et al. 2012; Poloczanska et al. 2013), show that, on average, seabird populations worldwide have not adjusted their breeding seasons over time or in response to sea surface temperature (SST) between 1952 and 2015 (see Keogan et al. 2018). However, marked between-year variation in timing observed in resident species and some Pelecaniformes and Suliformes (cormorants, gannets, and boobies) imply that timing, in some cases, is affected by unmeasured environmental conditions (Keogan et al. 2018).

How different seabird species will respond to coupled climate and ecosystem change is clearly related to many factors, including life history characteristics, food habits, range, and abundance (Furness and Tasker 2000). Some species may fare well in a warming ocean, whereas others may become locally, regionally, or perhaps even globally extinct (e.g., Kitaysky and Golubova 2000; Lewison et al. 2012). So overall, a fortunate number of factors, trophic position, global distribution, and numerous long-term studies, make seabirds a tractable and powerful group with which to study climate change in our oceans. Such an analysis allows us to not only make general inferences about the degree to which seabird ecology has changed both over time and in relation to SST (or other environmental variables) but also about the life history traits underpinning variation in ecological responsiveness. However, this profitable scenario is not equally distributed worldwide. A global view of the geographical distribution of seabird-climate change scenario shows that studies are concentrated in the NE Atlantic (North sea, Norwegian sea) and off the west coast of North America (California current to Gulf of Alaska). While studies are widely distributed, there are many regional oceans with little or no information, notably the tropical and subtropical regions (Sydeman et al. 2012). There are only two studies on how seabirds have changed over time and with climate in the Southwest Atlantic (SWA) between 40 and 50 south degrees (Quillfeldt et al. 2007; Millones et al. 2015). Of these, only one has focused on a seabird species from coastal Patagonia (Millones et al. 2015) (see below).

The Importance of the Long-Term Monitoring in a Global Change Scenario

Seabirds are widely recognized as reliable indicators of marine environmental changes (Velarde et al. 2019) associated with climatic as well as other anthropogenic and natural factors (see Durant et al. 2009 for a review). They are also relatively well studied compared to other marine organisms but are one of the most threatened groups of birds globally, and, overall, their conservation status is deteriorating rapidly (Croxall et al. 2012). Indeed ~25% of seabird species are currently listed as “threatened” or considered “of special concern” (IUCN 2020). Some seabird species that breed along coastal Patagonia, and forage in its jurisdictional area, are classified as “threatened” (Ministerio de Ambiente y Desarrollo Sustentable y Aves Argentina 2017). Moreover, many other seabird species that only forage in Argentinian waters are also threatened (wandering Albatross, grey-headed Albatross, and white-chinned petrel (Favero and Silva 2005)), and Argentina is one of the top ten ranked countries according to the number of seabird species of conservation concern (Croxall et al. 2012).

Since many seabirds face threats that may affect population status, the long-term monitoring of population, breeding, and behavioral parameters, preferably coupled with environmental data acquisition, is essential to assess how they respond to environmental changes and anthropogenic impacts (Bost et al. 2015). Long-term monitoring of seabirds, both at the breeding sites and at sea, is key to understand population drivers over time. Importantly though, a better understanding of the implications of changes in the marine and terrestrial environments for seabird species is required in order to improve their management and conservation status (Chambers et al. 2014).

In a global review, Sydeman et al. (2012) noted that most (85%) of seabird-climate studies reported on continuous (annual) data. Of the 108 references covered, they found a mean study period of ~23 years, with an average of ~20 years of data per study. The longest study covered 41 years (Sidhu et al. 2012). Most long-term research (88%) involved any of five seabird abundance or breeding parameters: reproduction (e.g., breeding success and other measures of reproductive performance), abundance, survival (of both adults and juveniles), phenology, and adult condition. Other measurements, which were more rarely investigated, included chick growth, community change, foraging behavior, and at-sea distribution (Sydeman et al. 2012).

Despite the auspicious global scenario in terms of long-term research described above, marine experts advise some degree of caution. Sydeman et al. (2012) pointed out that our interpretations are still limited because, despite having some of the best biological time series of the marine realm, seabird datasets are still of insufficient duration to separate natural inter-decadal variability from human-induced climate change effects. They strongly emphasize the need to maintain, and possibly enhance, existing long-term research and monitoring programs, even in times of financial limitations. These programs are necessary to develop the time series required to provide strong inference relating to seabird ecology under global change and most notably anthropogenic global warming (Sydeman et al. 2012). Such long-term empirical studies must focus on interdisciplinary research. Only through such an integrative approach will accurate predictions of change in seabird populations be possible, thereby facilitating seabird conservation in a changing world.

Background of Ecological Long-Term Studies in Patagonian Seabirds

Diversity, Abundance, and General Pattern of Distribution and Conservation Status

Coastal Patagonia breeding seabirds include species from five families, Spheniscidae (penguins), Procellariidae (petrels), Phalacrocoracidae (cormorants), Laridae (gulls and terns), and Stercorariidae (skuas), and constitute one of the best-studied groups of higher-trophic-level organisms in the Patagonian coast of Argentina. Seventeen seabird species breed along the 3,400 km coast from southern Buenos Aires (38° 58' S) to Tierra del Fuego (54° 50' S) (Fig. 1). This includes three penguins (Magellanic Penguin, *Spheniscus magellanicus*; Rockhopper Penguin, *Eudyptes chrysocome*; and Gentoo Penguin, *Pygoscelis papua*), one petrel (Southern Giant Petrel, *Macronectes giganteus*), five cormorants (Imperial Cormorant, *Leucocarbo atriceps*; Rock Shag, *L. magellanicus*; Red-legged Cormorant, *Poikilocarbo gaimardi*; Neotropical Cormorant, *Nannopterum brasilianus*; and Guanay Cormorant, *L. bougainvilliorum)*, three gulls (Kelp Gull, *Larus dominicanus*; Dolphin Gull, *L.*

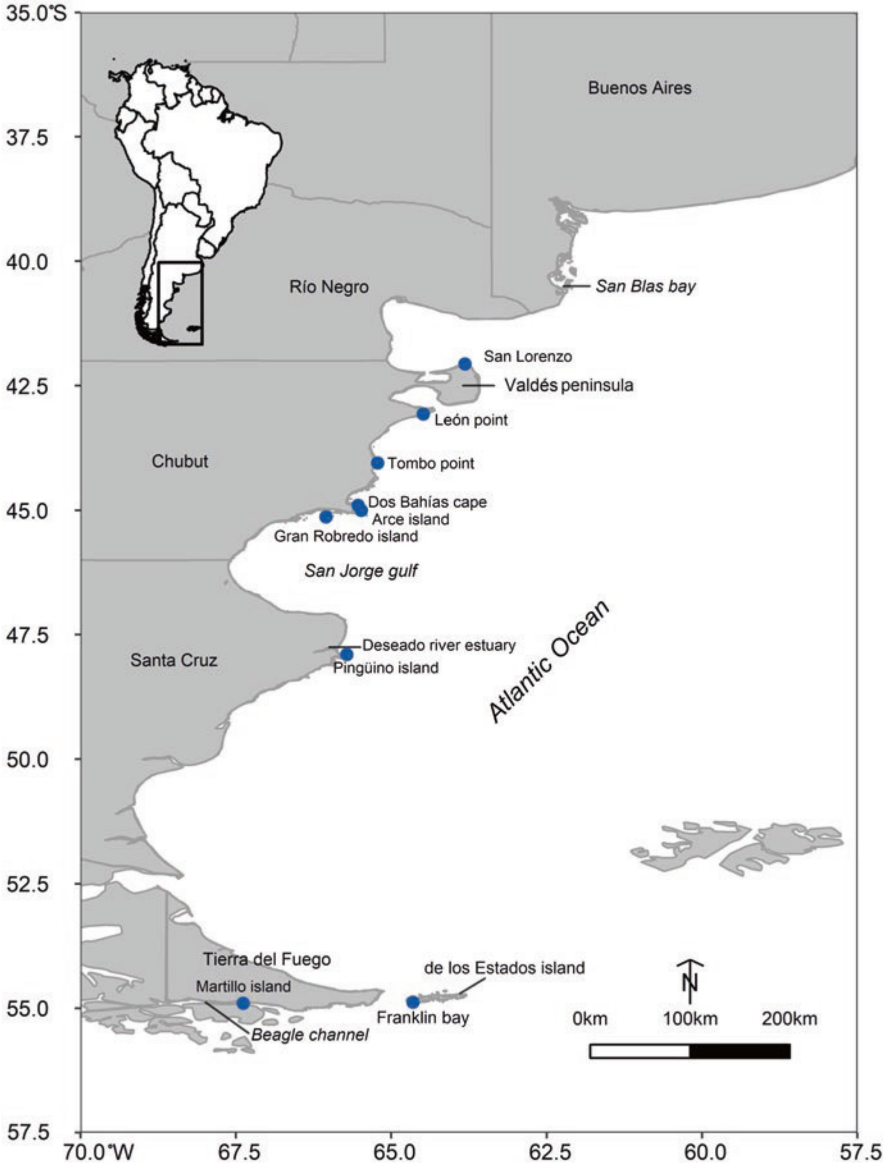

Fig. 1 Geographical location of Patagonian seabird colonies and other sites mentioned in the text

scoresbii; and Olrog's Gull, *L. atlanticus*), three terns (South American Tern, *Sterna hirundinacea*; Cayenne Tern, *Thalasseus eurygnathus*; and Royal Tern, *T. maximus*), and two skuas (Brown Skua, *Catharacta antarctica*, and Chilean Skua, *C. chilensis*) (Yorio et al. 1999; Yorio 2000). Almost the 70% of these species are not abundant and have breeding populations of less than 5,000 pairs (Yorio et al.

1999). The Magellanic Penguin is widely distributed (41° to 55° S) and is the most abundant with a breeding population size of more than one million pairs (BirdLife International 2020), an order of magnitude higher than all other Patagonian seabirds (Schiavini et al. 2005). The list is followed by the Kelp Gull and the Imperial Cormorant with more than 75,000 and 50,000 breeding pairs, respectively (Yorio 2000; Frere et al. 2005), chronologically and correspondingly wide distributions (38°–55° S). Other seabirds, such as the Red-legged Cormorant, the Olrog's Gull, and the Dolphin Gull, have a highly restricted distributions or nest in small colonies at a few sites in Argentina (Yorio et al. 1999). In addition to the 17 breeding seabirds, there are more than 40 non-breeding species which use the Argentine continental shelf as a foraging ground, mostly procellariiforms (Favero and Silva 2005). Despite the fact that the Patagonian coastal zone is one of the few relatively pristine coasts in the world, it is exposed at many locations to fast-growing economic activities such as commercial fisheries, tourism, urban and industry development, etc., with some uncontrolled actions linked to pollution, human disturbance, biological invasions, habitat degradation, and other threats for Patagonian seabirds (Yorio 2000).

In a global context, Southern Hemisphere countries are overrepresented in the number of seabird species of conservation concern, and yet long-term ecological information such as abundance, at-sea distribution, foraging effort, and breeding parameters of many Southern Hemisphere seabirds is limited to a few regions and species. In the Patagonian region, there is no substantial (and published) long-term ecological research with the exceptions detailed below.

Long-Term Research

Even when the ecology of Patagonian seabirds has been studied in a scientifically robust manner, there are only few clear, long-term ecology research approach (i.e., systematically maintained over a period of 10 years or more) in Argentina. Ecology-based research of seabirds inhabiting the Argentinian sea and its coasts has mainly been undertaken for limited periods (single or a few breeding seasons), probably because of logistical challenges of obtaining ecological data across years. Funding programs are also a clear constraint, with most research grants given for 1 to 5 years. Indeed, under the current recession in the global economy, it is hard to predict whether funding will be renewed. Here, we report on the existing long-term studies on seabirds of Argentina after a complete review of published data and personal contacts with seabird researchers who know of unpublished data and ongoing long-term research initiatives. We resume information as follows:

Penguins The Magellanic Penguin is by far the most studied seabird species seen from a long-term perspective, primarily due to the long-term research performed by Dee Boersma and collaborators at the Tombo point colony (44° 02' S, 65°11' W) (Fig. 1) since 1982. Breeding population numbers of this colony have declined 37% since 1987 (Pozzi et al. 2015; Rebstock et al. 2016). Breeding parameters such as breeding success, chick survival, chick growing rate, etc. have also been gathered since 1983 and reported under different research approaches (Boersma et al. 1990; Stokes and Boersma 1998, 2000; among others). At-sea movements and foraging variables (distances traveled and feeding trip durations) of adult breeders during the incubation and chick rearing periods have also been recorded for more than 10 years (Boersma and Rebstock 2009; Boersma et al. 2015). Although the Magellanic Penguin dataset is extensive, there is only one long term-based published article about the potential consequences of climate change on this species. Boersma and Rebstock (2014) studied the effect of storms (rains) on chick survival, based on long-term records of rainfall and air temperature. They found that during a period of 28 years, rain and heat are important sources of mortality in some years but are not the main cause of chick mortality, which was mainly affected by starvation and predation.

Other existing long-term initiatives with more than 5 years of data, including monitoring population numbers, breeding and demographic parameters, records of tagging birds, and foraging variables, are being collected at the Magellanic Penguin in Valdés peninsula (Quintana and Wilson, unpub. data) (see below), Dos Bahías cape (Blanco and Quintana unpub. data), Río Negro and Chubut colonies (Borboroglu et al. unpub. data), Santa Cruz colonies (Millones et al. unpub. data, Barrionuevo and Frere unpub. data), and the Beagle channel (Raya Rey et al. unpub. data) (but see Raya Rey et al. 2014) (Fig. 1).

Long-term studies targeting on the diet of the Magellanic Penguin seem to be reduced to systematic records of stable isotopes from adult breeders of Martillo island (54° 54’S, 67°23’W) (Dodino et al. unpub. data) and a diet study across years at the San Jorge gulf colonies (Yorio et al. unpub. data), both with less than 10 years of continuous data (Fig. 1).

The most comprehensive (in terms of number, quality, precision, and sample rate of the variables recorded) long term-based data series of the at-sea behavior of the Magellanic Penguin has been undertaken at San Lorenzo colony (42° 05’S, 63°51’W) in Valdés peninsula (Fig. 1) (Quintana and Wilson unpub. data, but see Sala et al. 2012, 2014; Wilson et al. 2015). Since 2008, more than 500 breeding adults have been instrumented with cutting-edge technologies to study at-sea distribution, diving behavior, prey capture, energy expenditure, and other indicators of the foraging effort of birds during the breeding season (Quintana and Wilson unpub. data). One of the relevant aspects of this long-term initiative is the use of advanced electronic technology for the study of animal behavior in relation to the environment. In fact, latest equipment allows the recording and quantification of environmental variables such as water temperature, depth, atmospheric pressure, and light with high precision (Sala et al. 2017). Thus, a comprehensive, long dataset of foraging movements and at-sea behavior can be coupled with oceanographic long-term records from operational oceanography, remote sensing, models, and/or bio-logging to link movement and/or foraging behavior with issues related with global change as well as other environmental consequences of anthropogenic-based stressors. In the current context of climate change and the rapid modification of the marine habitat, understanding the environmental factors that determine animal movements, behavior, and penguin at-sea distribution is becoming crucial to predict their ability to respond to changing conditions and ultimately the subsequent consequences on bird population dynamics (Fort et al. 2012). The consistent long-term database of the at-sea movement and behavior of the Magellanic penguin that is being built up, year after year, represents the seminal step for the next academic challenge: to analyze these data within the frame of a global change scenario.

The other two species of penguins breeding in coastal Patagonia, the Rockhopper and the Gentoo Penguin, have received less attention in long-term studies. The diet of both species has been monitored through stable isotopes over 10 and 8 years, at Franklin bay (54° 53' S, 64°39' W), de los Estados island, and the Beagle channel, respectively (Raya Rey et al. unpub. data) (Fig. 1). Population trends of the Rockhooper Penguin at the northern limit of its breeding range (Pingüino island, Santa Cruz, 47° 54' S, 65°43' W) (Fig. 1) have been studied for 35 years (1985–2020) with 27 years of census data (Gandini et al. 2017; Frere et al. unpub. data), and 16 years of unpublished breeding success data also exists for the same colony (Morgenthaler et al. unpub. data). Population numbers of a newly established colony of Gentoo penguins at Martillo island (Fig. 1) have been continuously monitored since 2000 (Raya Rey et al. 2014; unpub. data).

Cormorants The Imperial Cormorant is the only species of cormorant that has been comprehensively studied using a long-term research approach at a single colony in Patagonia, Argentina. Breeding parameters and the pelagic ecology of the Imperial Cormorant have been systematically studied since 2004 by some authors of this chapter. In the section below, we present, as a case study, our original data and results of this long-term study through time. Over 16 years, we examined the inter-annual variability of breeding and foraging variables of birds from León point, Chubut (43° 04' S, 64° 29' W) (Fig. 1), one of the two biggest colonies (> 6,000 pairs) of the species in its breeding range in coastal Patagonia Argentina (Frere et al. 2005). In addition, over 26 years, Yorio et al. (2020) have recently reported population numbers of Imperial cormorants in northern coastal Argentine Patagonia. Occasional data of breeding population numbers have also been reported for colonies from the Beagle channel (see Raya Rey et al. 2014).

The other existing long-term population data of a Patagonian cormorant species is maintained by E. Frere and collaborators for the Red-legged Cormorant from Santa Cruz colonies. Published data on its population trends for a period of 20 years appear in Millones et al. (2015), and the effect of oceanographic conditions (SST and chlorophyll-a) on these trends was analyzed, suggesting that coastal ocean productivity could be an important factor affecting temporal variations in the Argentinian Red-legged Cormorant population.

Petrels Population numbers of the Southern Giant petrels breeding in northern Patagonia, Argentina (Arce island 45° 00' S, 65° 29' W and Gran Robredo island 45° 08' S, 66° 03' W) (Fig. 1) have been monitored since 1987, and petrel population trends were reported up to 2004 by Quintana et al. (2006). Annual data of breeding pairs and total number of fledgling have been systematically gathered since 1995 (Quintana and Blanco, unpub. data).

Other Species and Multispecies Approaches In general terms, species pertaining to the other Patagonian seabird families (Laridae (gulls and terns) and the Stercorariidae (skuas)), are the least studied over the long term. The most extensive breeding population record of the abundant and widely distributed Kelp Gull is over 7 years for at only three of the 68 northern Patagonian colonies of Río Negro and Chubut provinces (Lisnizer et al. 2011). Breeding population numbers of Dolphin Gull colonies from the Deseado river estuary, Santa Cruz (Fig. 1), have been annually monitored since 2007 to the present (Millones et al. unpub. data) and few occasional counts (four over 20 years) reported by Raya Rey et al. (2014) at the two colonies in the Beagle channel. The foraging areas and other feeding parameters of Olrog's Gull were determined at San Blas bay, south of Buenos Aires (39° S, 61° W) (Fig. 1) for a 5-year period (Suarez and Yorio, unpub. data). There are no medium-/long-term records of any ecological variable for the three species of terns and the two species of skuas from coastal Patagonia Argentina.

Long-term multispecies approaches only relate to the seabird-fisheries interactions. Favero et al. (2013) reported the seabird bycatch in the Argentinian demersal longline fishery for a 10-year period (2001–2010). They characterized, in space and time, the occurrence and intensity of seabird mortality as consequence of the interaction with demersal longline fisheries operating in the Argentine Sea. However, their long-term database extends over the period 1999–2019 and includes bycatch of seabirds in other types of fisheries and related operational and environmental variables (i.e., wind, sea state, etc.) (Favero et al. unpub. data).

In summary, long-term ecological research approaches are not common in Argentina. Only two species (the Magellanic Penguin and the Imperial Cormorant) from single colonies have been systematically studied for continuous period > 10 years in a broad sense (i.e., not only population counts). Even the few existing long-term population data of these and other species are focused on a single species at a particular location/area, and population trends are based on sporadic counts over time, having to resort to mathematical models to present population data with confidence.

Although the non-breeding period is critically important for the population dynamics of seabirds since most mortality occurs at this time (Frederiksen et al. 2008), the few long-term studies on Patagonian seabirds are usually undertaken during the breeding season. Thus, a key question in understanding the link between global change and/or prey availability and seabird ecology is the extent to which there have been long-term changes in both breeding and non-breeding season's ecological variables.

To our knowledge, almost no published studies have quantified long-term trends in any ecological variable other than breeding population numbers in Patagonian seabirds (but see some on the Magellanic Penguin above), and almost no study has compared long-term trends with environmental changes over time (but see Millones et al. 2015). Indeed, our understanding of the spatial ecology of Patagonian seabirds facing environmental change is very rudimentary, despite its relevance for the conservation of these vulnerable organisms and for the management of South Atlantic marine ecosystems. It is thus clear that long-term-based research on seabirds must be continued and results interrogated (including the development of new approaches) to integrate processes occurring at various scales, so as to track the population responses of these long-lived vertebrates to environmental changes.

In the next section, we offer unprecedented results from a long-term dataset (16-year period) on demographic, breeding, and at-sea ecological variables for the imperial cormorant from León point, Chubut. Our research is given only as an example of the database gathered under a long-term ecological research needed to understand the potential effects of global change on Patagonian seabirds.

A Model of Long-Term Ecological Research on a Patagonian Seabird: The Imperial Cormorant

As mentioned, it is only recently in Argentina that seabird ecology studies have focused on inter-annual variability over the long term. Such long-term studies are necessary if we want to have a better understanding of how birds make use of the surroundings of a breeding colony (Corman et al. 2016; Warwick-Evans et al. 2016) because this will help us identify important areas for conservation in the form of marine protected areas or other management and conservation tools (Thaxter et al. 2012). Long-term approaches integrating population and breeding parameters with at-sea performance are as rare as they are essential, even when they are key to wholly understanding the status and health of seabird populations (Inchausti et al. 2003).

The Imperial Cormorant colony of León point is one of the two largest colonies (> 6,000 pairs) of the species at its breeding range in coastal Patagonia Argentina (Frere et al. 2005). Previous studies performed at this breeding site have analyzed several aspects of the bird's at-sea distribution and diving and foraging behavior by means of miniaturized data loggers (Global Positioning System, time depth recorders, daily diaries, and accelerometers; Shepard et al. 2009; Quintana et al. 2011; Wilson et al. 2012; Gómez-Laich et al. 2013; among others). Most of these studies have been focused on specific behaviors related to diving performance and energy management, among others, with no more than 2 or 3 years of data. In the present work, we capitalize on a long-term data series (i.e., 14 years of records over a 16-year period from 2004 to 2019) including breeding parameters and foraging patterns, to describe inter-annual variation. Firstly, we examine the variation over time of some foraging trip parameters, the use of marine habitat, and the foraging range of both males and females. Secondly, we examine how both sexes exploited the depth-dependent "energy landscape" (landscape-dependent energy expenditure, see Wilson et al. 2012) of the area around the colony over time, and thirdly, we analyze the inter-annual variations of some breeding parameters. We then discuss the importance of long-term tracking, breeding, and population data for ecological studies and their implications for conservation and management plans.

At-Sea and Breeding Performance Data Gathered Through Time

Fieldwork was conducted at León point colony (43° 04’ S, 64° 29’ W), Chubut, Argentina (Fig. 1) over 16 breeding seasons (in late November–early December of 2004–2019). A total of 567 Imperial cormorants brooding chicks < 10 days old were fitted with GPS loggers. Of those, 207 were equipped with GPS loggers (Earth and Ocean Technologies, Kiel, Germany), 229 were fitted with Mini-GPS loggers (Earth and Ocean Technologies, Kiel, Germany), six were instrumented with GiPSy-4 loggers (TechnoSmart, Rome, Italy), and 125 were fitted with Axy-Trek loggers (TechnoSmart, Rome, Italy) (Table 1). All of the devices were programmed to record time, latitude, longitude, and ground speed (GPS-based) every second. Each animal was sexed by its vocalizations following Svagelj and Quintana (2007) and gently removed from its nest using a specially designed pole with a crook. Devices were attached to the feathers of the lower back using Tesa tape following procedures outlined in Wilson et al. (1997) and retrieved after ≤ 24 h. All of the equipped birds continued to breed normally during the study period.

Only completed foraging trips (departure from and arrival to the nest) were included in the analyses. Most cormorants performed a single foraging trip before the logger was retrieved; however a small number of individuals (< 5%) performed two or more trips. In these cases, only the longest trip performed by the animal was considered for further analyses to avoid pseudo-replication. Identification and classification of the different behaviors performed by cormorants in each of the foraging trips were described in Quintana et al. (2011). Fixes were categorized into three classes: traveling (flying), floating, and diving (see Quintana et al. 2011 for details). This classification allowed us to calculate a series of five foraging trip parameters for each bird composed of: (1) times (in h), trip duration (from departure until returning to the colony) and total foraging duration (time between the first foraging dive until the last); (2) distances (in km), foraging path length (total distance traveled) and commuting distance (distance from the nest to the first dive plus the distance from the last dive to the nest); and, finally, (3) the number of dives per total foraging time. During 2014, devices did not record data in exactly in the same regime as the other years, and we only computed data of total trip duration, total distance traveled, and commuting distance (see Table 1).

To describe the pattern of variation of each studied variable across years, we calculated an overall mean which was obtained by calculating the weighted mean of yearly means using the *weightedMean* function from the R library *matrixStats* (R Core Team 2019). The latter was used because the number of samples differed significantly between years and we wanted each year’s mean to contribute the same to the overall mean. Since at-sea movements and behavior differ between males and females (Quintana et al. 2011; Gómez-Laich et al. 2012), overall mean calculations were performed for males and females separately. After this, for each bird, we calculated the difference between each foraging trip parameter and the overall mean

Table 1 Total number of instrumented Imperial cormorants and recorded tracks during a 16-year period. The mean value and the standard deviation of the total trip duration, the foraging time, the total distance traveled, the commuting distance, and the number of dives per hour per sex per year are also shown

Year	Sex	Total instrumentations	Tracks with data	Trip duration (h)	Foraging time (h)	Total distance traveled (km)	Commuting distance (km)	Number of dives per hour foraging
2004	Female	8	7	5.53 ± 2.53	4.4 ± 2.0	60.3 ± 28.7	33.4 ± 16.0	14.3 ± 3.2
2004	Male	8	7	6.06 ± 1.49	4.4 ± 0.8	93.6 ± 47.6	41.3 ± 12.9	13.5 ± 4.9
2005	Female	8	8	6.73 ± 1.91	5.2 ± 1.7	74.8 ± 30.6	35.4 ± 15.0	25.6 ± 12.8
2005	Male	8	6	5.18 ± 0.95	4.1 ± 0.6	64.0 ± 22.8	21.1 ± 13.6	11.8 ± 4.1
2007	Female	8	5	5.75 ±1.36	2.3 ±0.6	90.3 ± 25.1	65.2 ± 23.2	19.9 ± 13.9
2007	Male	7	5	4.49 ±0.81	2.1 ±0.4	68.5 ±20.1	35.2 ±17.1	17.4 ±6.7
2008	Female	22	18	6.61 ± 1.28	5.3 ± 1.1	64.8 ± 22.5	28.6 ± 10.8	11.5 ± 3.2
2008	Male	20	15	6.53 ± 1.40	5.1 ± 1.3	75.3 ± 15.3	19.5 ± 7.6	22.1 ± 11.3
2009	Female	31	13	6.18 ± 1.97	4.3 ± 1.5	69.8 ± 27.2	27.3 ± 15.8	13.9 ± 4.0
2009	Male	30	16	4.56 ± 2.16	3.6 ± 1.9	53.7 ± 24.4	16.6 ± 9.9	20.1 ± 8.9
2010	Female	48	25	7.47 ± 1.27	5.9 ± 1.2	78.6 ± 25.0	40.9 ± 18.4	13.6 ± 4.0
2010	Male	50	24	5.88 ± 1.46	4.3 ± 1.5	75.4 ± 33.0	26.1 ± 14.2	15.8 ± 7.2
2011	Female	29	11	7.93 ±1.34	6.1 ±1.0	68.0 ±23.1	38.1 ±21.6	12.2 ±2.4
2011	Male	13	6	6.48 ±0.52	5.1 ±0.8	68.7 ±13.6	28.8 ±6.2	18.8 ±11.3
2012	Female	15	10	10.14 ± 1.70	4.8 ± 1.6	72.1 ± 30.1	38.6 ± 16.7	20.1 ± 16.0
2012	Male	15	7	8.89 ± 2.63	4.5 ± 1.7	70.3 ± 16.4	24.9 ± 10.3	12.1 ± 4.1
2013	Female	18	10	6.15 ± 1.34	4.6 ± 1.3	68.8 ± 22.2	37.1 ± 14.0	15.7 ± 8.3
2013	Male	21	12	6.22 ± 1.81	4.2 ± 1.3	71.5 ± 22.2	35.8 ± 16.5	16.8 ± 9.1
2014	Female	20	6	6.50 ± 0.91	-	76.7 ± 14.4	41.3 ± 15.7	-
2014	Male	21	7	7.38± 0.47	-	63.2 ± 12.8	38.6 ± 15.0	-

(continued)

Table 1 (continued)

Year	Sex	Total instrumentations	Tracks with data	Trip duration (h)	Foraging time (h)	Total distance traveled (km)	Commuting distance (km)	Number of dives per hour foraging
2015	Female	19	17	6.46 ± 1.40	5.1 ± 1.2	78.8 ± 20.8	31.2 ± 15.7	15.8 ± 11.6
2015	Male	21	14	6.61 ± 2.88	3.2 ± 1.7	67.3 ± 27.5	36.3 ± 13.7	16.7 ± 8.6
2016	Female	32	15	6.87 ± 1.38	5.5 ± 1.2	81.6 ± 22.9	22.8 ± 13.3	12.8 ± 3.8
2016	Male	28	16	5.43 ± 1.60	4.2 ± 1.3	70.8 ± 15.8	29.2 ± 8.1	8.0 ± 2.0
2017	Female	21	12	8.72 ± 1.38	7.4 ± 1.5	73.3 ± 29.3	31.6 ± 20.5	17.3 ± 4.7
2017	Male	20	16	5.65 ± 2.23	4.0 ± 2.4	96.3 ± 18.2	44.1 ± 12.8	15.7 ± 6.1
2019	Female	12	8	6.97 ± 1.07	5.3± 0.9	59.5 ± 28.6	30.9 ± 19.1	11.8 ± 4.2
2019	Male	14	9	5.66 ± 1.62	4.3 ± 1.5	75.4 ± 20.9	38.0 ± 15.4	9.8 ± 4.3
	Female weighted mean			7.0 ± 1.20	5.1 ± 1.1	72.7 ± 8.1	35.9 ± 9.7	15.7 ± 3.9
	Male weighted mean			6.14 ± 1.03	4.1 ± 0.8	72.4 ± 10.8	31.0 ± 8.3	15.3 ± 3.9

for that parameter (hereafter, deviation from the overall mean), and this difference was used in the following analyses.

Kernel analyses to assess habitat use from GPS locations were performed for each year by sex using the fixed kernel density estimator (FKDE, KernelUD function in the R package adehabitatHR, Calenge 2006). We considered the 95, 75, and 50% fixed kernel probability density to represent areas of active use (home range area, HRA) (Hamer et al. 2007). The smoothing parameter (h) was set to 0.012 and the cell size was of 1 km^2. We distinguished between mean home range and mean foraging area used per sex per year by calculating the 95% fixed kernel probability density of each of the instrumented animals. To calculate the mean home range, we used all the GPS positions, while only those positions classified as dives were considered to determine the mean foraging area. Finally, we quantified the annual overlap of the foraging areas between sexes. The degree of overlap was calculated as the percentage of the 95% kernel foraging area used by males that overlapped with those used by females and vice versa. Since the total area from which the percentage was calculated was different for each sex, we calculated a percentage overlap for males with respect to females and a percentage overlap for females with respect to males (Gonzáles-Solís et al. 2000).

Bird locations classified as dives were overlaid over an energy landscape scenario that considered the cost of transport based on the costs of flying to and from the colony to the foraging grounds and the costs of foraging along the seabed (mass-specific energy invested per second, J kg^{-1} s^{-1}, see Wilson et al. 2012). For each year, the density of dives (number of dives per km^2) performed in each of the different energy-demanding environments surrounding an area of 60 km (corresponding to the maximum distance from the colony reached by the tagged birds) around the colony was calculated.

Finally, breeding parameters were collected from a total of 2,553 nests. Over 14 breeding seasons, nests were visited every 3–5 days from the start of the laying period until chicks reached 30 days of age (Svagelj and Quintana 2011). Chicks were considered to have fledged (breeding success) if they reached 30 days of age, due to the high probability of chick survival to independence at that age (Svagelj and Quintana 2011).

For each trip parameter and sex, differences between years in the deviation from the overall mean were tested by means of one-way analysis of variance (ANOVA) using the *aov* function from the stats R package. Only in the case of the number of dives per foraging hour, male's home range and male's foraging area, were Kruskal-Wallis tests performed using the *kruskal.test* function from the stats R package. Finally, multiple comparisons were performed using the *lsmeans* function from the lsmeans R package or the *dunnTest* function from the FSA R package. All algorithms, plots, and statistical tests were performed using the open source statistical software R version 3.6.1 (R Development Core Team 2019) with a level of significance $p< 0.05$. Results of foraging parameters are shown as mean ± standard deviation (SD).

Foraging Trips and Use of Marine Areas Over Time

We recorded a total of 325 complete foraging trips from breeding adults. Of these, 165 (51%) were performed by females and 160 (49%) by males. Since several GPS devices failed to record data, no foraging information was obtained for 2006 and 2018 breeding seasons.

Most adult breeders made a single foraging trip per day to find food for themselves and the offspring. The overall mean foraging trip duration for females and males was 7.0 ± 1.2 h and 6.1 ± 1.0 h, respectively (Table 1). The foraging trip duration was relatively steady across the study period (Fig. 2A, B). In general, yearly foraging trip duration for males and females was similar to the overall mean, except during 2012. During this particular year, males remained at sea 2.8 h longer than average (year effect $p<0.01$, $F_{13,146}=2.7$). As regards females, daily feeding excursions were 3.1 and 1.7 h longer than the overall mean during 2012 and 2017 (year effect $p<0.01$, $F_{13,151}=6.8$, Tukey contrasts between 2012 and the rest of the years but 2017, $p<0.03$; Tukey contrasts between 2017 and 2004, 2007, 2008, 2009, 2013 $p<0.02$), respectively (Fig. 2A). Females always spent more (or equal) time at sea than males, except in 2014 when we recorded the opposite pattern (Fig. 2A).

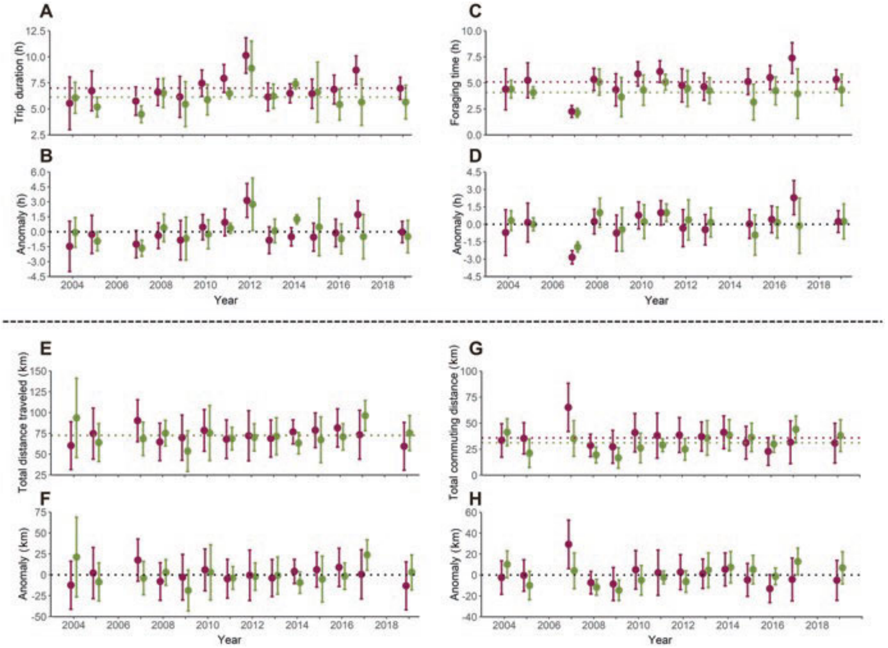

Fig. 2 Foraging parameters (mean ± standard deviation (SD)) over time (a 16-year period) of adult breeders (females in purple circles and males in green circles) of Imperial cormorants from León point, Chubut, Argentina. (**A**) Duration of foraging trips, (**C**) foraging time at sea, (**E**) total distance traveled, and (**G**) commuting distances to and from the foraging sites. Annual deviations from (**B**) trip duration overall mean (i.e., anomaly), (**D**) foraging time overall mean, (**F**) total distance traveled overall mean, and (**H**) the commuting distance overall mean

In general terms, the foraging time at sea was also relatively stable along the 16-year period, and females never spent less time foraging than males (Fig. 2C, D). While at sea, female Imperial cormorants foraged on average 5.1 ± 1.1 h, while males spent 4.1 ± 0.8 h. A clear anomaly of the, otherwise, regular foraging pattern was particularly evident for females during 2007, when birds spent less time foraging than all other years (Fig. 2C). In 2007, female foraging time was 2.8 h less than the overall female mean (Tukey contrasts between 2007 and the rest of the years but 2004, 2009, and 2013, p values <0.03) (Fig. 2C). By contrast, during 2017 (in a manner similar to that observed for trip duration), females spent a particularly great amount of time foraging at sea (2.3 h more than the overall mean) (Tukey contrasts between 2017 and the rest of the years but 2010 and 2011, all p values <0.02) (Fig. 2C).

Total distances covered by adult Imperial cormorants during the at-sea foraging excursions were very consistent over the study period (Fig. 2E, F). The overall mean for females and males was 72.7 ± 8.13 and 72.4 ± 10.8 km, respectively. Females were more consistent than males with respect to the total distances covered while at sea. Contrary to the males, females did not have any distinctive value emanating from particular years (females year effect p=0.4, $F_{13,151}$=1.0; males year effect p<0.01, $F_{13,146}$=2.6), while the total distance traveled by males was particularly high during 2004 and 2017 (23.9 and 21. 2 km above the overall mean) and particularly low during 2009 (18.8 km below the overall mean) (male Tukey contrasts between 2004–2009 and between 2009–2017, p=0.02 and p<0.01, respectively) (Fig. 2E).

The flying distances covered by birds during commuting to and from the foraging areas were also relatively constant across seasons (Fig. 2G, H), and the overall mean for females and males was 35.9 ± 9.7 km and 31.2 ± 8.3 km, respectively. Male commuting distance was particularly low during 2008 and 2009 (11.7 and 14.5 km below the overall mean, respectively) and higher during 2017 (12.9 km above the overall mean) (year effect p<0.01, $F_{13,146}$=5.8, Tukey contrasts between 2008 and 2015, 2017 and 2019, all p values <0.03; Tukey contrasts between 2009 and 2004, 2013, 2014, and 2017, all p values <0.02) (Fig. 2G). By contrast, it was only during 2007 that females showed any distinctively higher value for their commuting distance (29.3 km above the overall mean) (year effect p<0.01, $F_{13,151}$=2.8, Tukey contrasts between 2007 and 2008, 2009, 2015, 2016, 2017, and 2019, p values<0.03).

Finally, over the study period, the number of dives performed per hour foraging was less regular than the other foraging variables (Fig. 3A, B). In some years, males performed more dives per unit time foraging at sea than females, although the opposite pattern was also evident. On average, female and male foraging cormorants performed 15.7 ± 3.9 and 15.3 ± 3.9 dives per hour, respectively. Deviations from the overall mean were evident for males during 2016 (7.3 dives per hour below the overall mean) (year effect p<0.01, K-W χ_{212} = 44.2) (Fig. 3A). In the case of females,

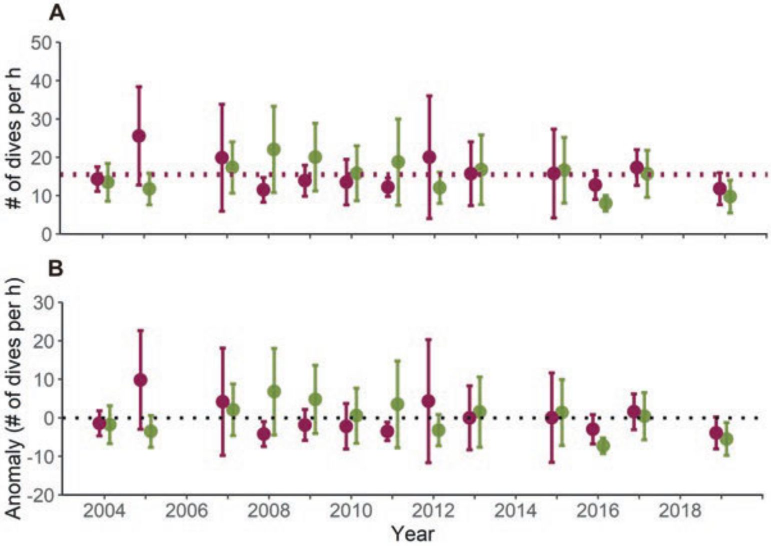

Fig. 3 Number of dives per foraging time (mean ± standard deviation (SD)) of adult breeders (females in purple circles and males in green circles) of Imperial cormorants from León point, Chubut, Argentina, annually performed during a 16-year period (**A**) and annual deviation from the overall mean (anomaly) (**B**)

the number of immersions per hour varied considerably between years (year effect $p = 0.03$, K-W $\chi_{212} = 22.8$). Female diving rate was the highest during 2005 (9.8 more dives per hour than average) and the lowest during 2008 (4.2 fewer dives per hour than average) (Fig. 3A).

Imperial cormorants from León point always foraged within 60 km of the colony and mostly in waters <50 m depth (Fig. 4). A view of all at-sea positions (data for all years together) showed that both females and males from León point exclusively used waters south of the colony to forage at sea (Fig. 4).

From 2004 to 2019, females spread (indicated by the 95% kernel contour) over an average area at sea of 217.4 ± 32.2 km^2 and their home range was very consistent across years ($F_{12,146} = 1.2$, $p = 0.3$) (Fig. 5A, B). Males used a similar area to the females (227.1 ± 43.4 km^2), but deviations from the overall mean were evident during 2009 and 2017 (76 km^2 below and 100 km^2 above the overall mean, respectively) (K-W $\chi_{12} = 23.2$, $p = 0.03$) (Fig. 5A, B).

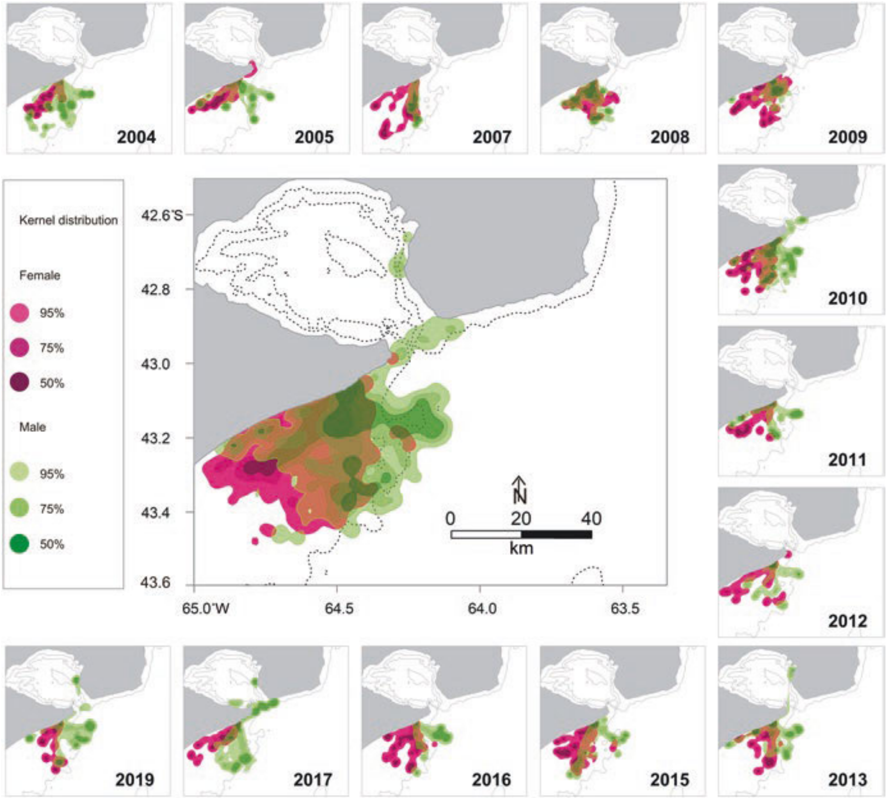

Fig. 4 Imperial cormorants, *Leucocarbo atriceps*. Kernels encompassing 50% (light green), 75% (medium green), and 95% (dark green) of male's and 50% (pink), 75% (medium purple), and 95% (purple) of female's foraging locations from León point between 2004 and 2019. The central map encompasses data from all years in one plot

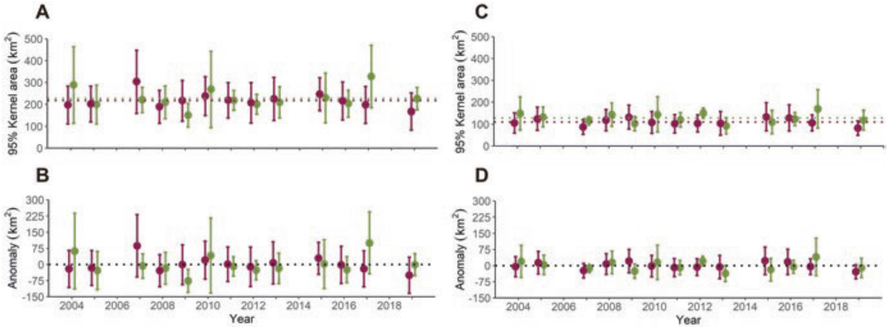

Fig. 5 At sea and foraging areas (mean ± standard deviation (SD)) over time of adult breeders (females in purple circles and males green circles) of Imperial cormorants from León point, Chubut, Argentina. (**A**) Annual variation of the at-sea areas (95% kernel contour of all at-sea-positions) and (**C**) annual variation in the foraging areas (95% kernel contour of dive positions). Annual deviations from (**B**) the at-sea area overall mean (i.e., anomaly) and (**D**) the foraging area overall mean are also shown

Both sexes exhibited some grade of consistency in the use of the foraging areas (given by the 95% kernel contour of foraging locations) along the whole study period (Fig. 5C, D). Females spread out over an average foraging area of 110.5 ± 15.6 km^2 and showed a high consistency across seasons ($F_{12,146} = 1.1$, $p=0.4$) (Fig. 5B). Similarly, the average size of the feeding area used by males was 128.6 ± 21.1 km^2 with no anomalies across time (K-W $\chi_{12} = 20.9$, $p=0.05$) (Fig. 5C, D).

Male Imperial cormorants commonly foraged offshore, to the south-east and near the 50 m isobaths, while females foraged closer to the coast in shallower waters located southwest of the colony. This pattern of sexual segregation in the use of foraging grounds was evident across breeding seasons (Fig. 4). However, foraging females and males overlapped marginally in their foraging areas in every season (mean, 27.7 ± 14.9 and 28.3 ± 20.7% for females over males and males over females, respectively), with a maximum overlap during 2008 and 2009 (Fig. 6A, B).

Based on 22,056 foraging dives, we found that over the complete study period, Imperial cormorants mainly foraged in a virtually homogenous energy landscape (i.e., landscape-dependent energy expenditure, see Wilson et al. 2012) corresponding to the least energetically costly areas (Fig. 7). Overall, females and males concentrated 96–97% of their dives in an area represented by the three least costly fields (Fig. 7). This pattern was also very consistent along the years (Fig. 8). While females systematically foraged mainly on the least costly field (level 1) (Fig. 8A), males allocated their foraging activities equally between the three first energy landscape levels (Fig. 8B). Only between 2008 and 2010 was the number of dives performed per km^2 by males highest in the first field than in the other two (Fig. 8B).

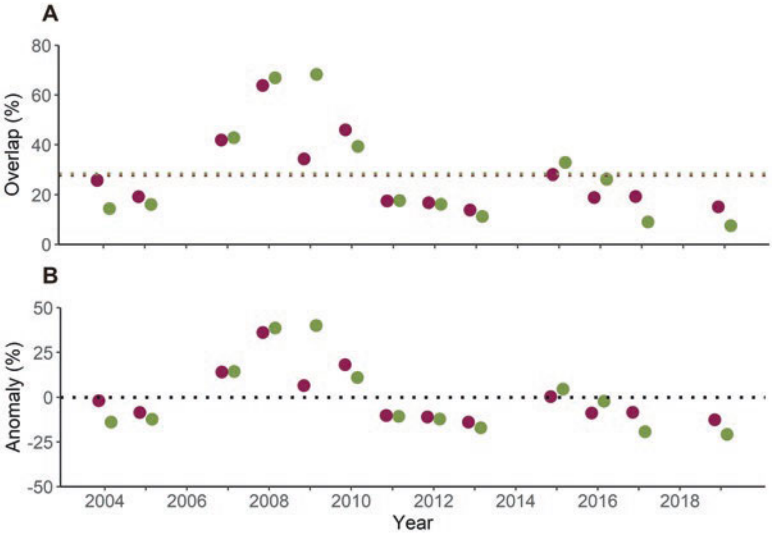

Fig. 6 Annual variation of the spatial overlap (%) in the foraging areas over time of adult Imperial cormorants from León point. (**A**) Overlap of females over males' foraging areas is showed in purple circles at those of males over females in green circles and (**B**) annual deviation from the spatial overlap overall mean (anomaly)

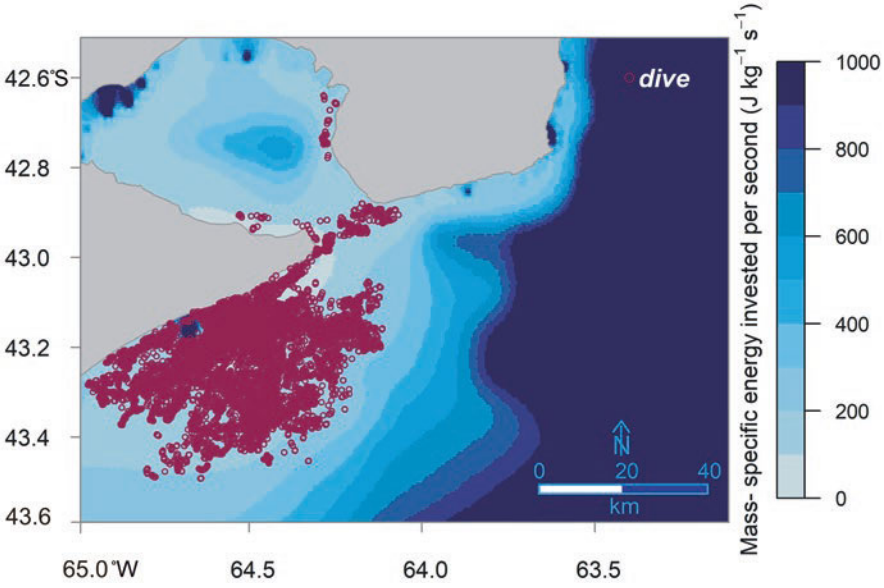

Fig. 7 Use of the energy landscape in the colony surroundings by adult Imperial cormorants breeding in León point. Foraging dives from 2004 to 2019 are represented by purple dots overlaid in the energy levels of the marine landscape (from least energy costly, light blue, to most energy costly, dark blue) (see text)

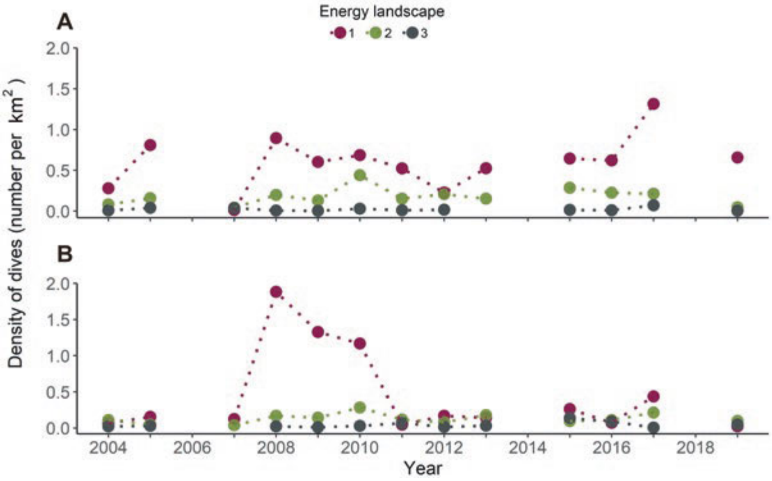

Fig. 8 Annual variation of the number of dives per km^2, performed at the three least costly fields (level 1 to 3) of the energy landscape, by female (**A**) and male (**B**) adult Imperial cormorants of León point during a 16-year period

Breeding Performance and Phenology Through Time

The clutch size and laying date (and consequently hatching date) of Imperial cormorants was very consistent across years (Fig. 9A–D). Mean clutch size for a 16-year period was 2.7 ± 0.6 (range, 2.5–2.8) (Fig. 9A, B). Delays or advance dates of 10 days in laying were very infrequent and were observed in only two breeding seasons (2005 and 2010, respectively) (Fig. 9C). Almost 60% of breeding seasons showed delays or advance dates < 5 days (Fig. 9D). The mean breeding success for the whole study period was 0.9 ± 0.7 chicks per nest and was also extremely consistent across breeding seasons. A clear decrease in breeding success was evident for 2016 (Fig. 9E, F).

Insights and Discussion on the Imperial Cormorant Long-Term Study

In this section we reported, for the first time, the long-term variability of phenology (timing of breeding), breeding traits (clutch size and breeding success), at-sea distribution, and foraging effort (foraging distances, trip duration, number of dives, etc.) of breeding Imperial cormorants from one of the largest colonies (more than 6,000 breeding pairs) of the species along its breeding range in coastal Patagonia, Argentina. These variables have been identified as key response types from previous

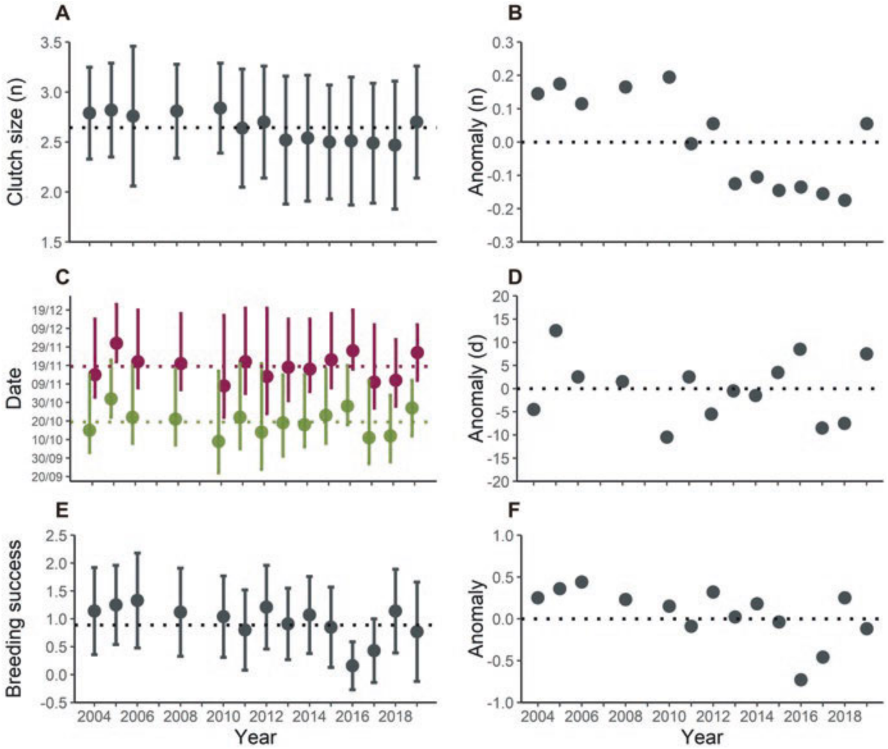

Fig. 9 Annual variation (mean ± standard deviation (SD)) of (**A**) clutch size, © laying (in green) and hatching (in purple) date, and (**E**) breeding success of the Imperial cormorant at León point over 16 breeding seasons. Annual deviations from (**B**) the clutch size overall mean (anomaly), (**D**) hatching date overall mean, and (**F**) breeding success overall mean are also showed

ecological investigations of climate change and other impacts on seabird populations worldwide (Sydeman et al. 2012). Our long-term initiative started at 2004 season recognizing that long-term tracking data coupled with breeding parameters can be employed to obtain ecological indicators about the status of a population (see Grémillet et al. 2006; Lewis et al. 2006).

Long-Term Variability in Foraging Parameters We found a consistent general pattern in the foraging parameters studied over our 16-year period. Both females and males foraged along seasons by performing an almost invariable feeding routine. The number of trips per day, trip duration, foraging time, distances covered while at sea, and the number of dives were particularly consistent over more than one decade in the study area. The long-term stability observed in foraging parameters might be a combination of both intrinsic and extrinsic factors, and the few anomalies recorded seem erratic and difficult to elucidate.

In the particular case of cormorants, intrinsic factors are likely mainly related with the high energy costs associated with flying, which preclude these birds from traveling far (Watanabe et al. 2011). As a consequence, an increase in the time spent flying to and from the colony to the foraging grounds represents a substantial increase in the energy expenditure of the complete foraging trip. For Imperial cormorants, it has been suggested that flying is the most expensive activity that occurs at sea with as much as 42% of the total energy invested during a foraging trip being spent commuting to and from the feeding grounds (Gómez-Laich et al. 2013). Therefore, the energy expenditure associated with this activity will likely restrict the birds both in terms of distances traveled during foraging trips and the distances covered during the breeding season. Superimposed upon this, learned skills, acquired over time, would allow older cormorants to exploit specific profitable foraging areas repeatedly (Patrick et al. 2013; Harris et al. 2014).

Seabird's at-sea behavior is also known to be modulated by extrinsic factors, such as competition for resources (Corman et al. 2016) or changing environmental conditions (Patrick et al. 2013). Our long-term data for the Imperial Cormorant in León point showed that foraging trip duration (and other related foraging variables) was relatively constant across the study period (Fig. 2A, B) and did not show any decrease over time, even the breeding population doubles from 3,000 to 6,100 pairs between 2004 and 2019 (Yorio et al. 2020; Quintana et al. unpub. data). These findings suggest that the Imperial Cormorant from León point is not subject to competition, perhaps because they exploit a predictable and abundant source of food in the vicinity of the colony.

Spatial Consistency of the Foraging Areas and the Energy Landscape Our long-term records showed clear spatial consistency in how chick-rearing Imperial cormorants use the coastal-marine habitat. In general, both female and male foraged primarily within 60 km off the colony in waters < 50 m deep (Figs. 4 and 7). Nevertheless, as indicated by previous studies (Quillfeldt et al. 2011; Quintana et al. 2011), we found clear sexual segregation in the use of foraging areas over time. Even though females generally foraged closer to the coast and males in deeper offshore waters, there was, however, consistent slight overlap in their foraging areas across breeding seasons. The maximum foraging overlap (> 70%) occurred during 2008 (females with respect to males and vice versa) and 2009 (only males with respect to females) (Fig. 6). It has been suggested that intraspecific competition for prey and resources would force this species to develop notable plasticity in their foraging behavior, which would be generally expressed via habitat segregation by sex (Quintana et al. 2011) and/or realized by sex-specific (body-size-driven) physiological differences in diving capacity with respect to depth (Gómez-Laich et al. 2012). However, this elegant and presumably normal, optimal scenario would change if foraging birds have to cope with unusual environmental change, as likely happened during 2008 and 2009 seasons.

Our long-term results on the consistency of foraging areas across years are in accordance with previous findings obtained over 4 years by Harris et al. (2014). The observed repeatability across seasons in the use of foraging areas (and behavior) may be due to a combination of individual characteristics such as learning abilities, breeding experience, and/or health condition, as well as targeted prey type and stability of the environment at this location. Evidence of high consistency in the use of foraging areas among seasons reinforces the notion that the oceanic environment surrounding the colony (Acha et al. 2004; Rivas and Pisoni 2010) and targeted prey are stable across successive breeding seasons. This enables individuals to be successful if they behave consistently, even over the long term. Indeed, our data series highlights the idea of the stability and a predictability of the food source exploited by the Imperial cormorants in this region of coastal Patagonia, reflecting general environmental stability close to the colony. The viability of repeated use of a given foraging area by individuals will depend primarily on how stable the targeted prey system is over time (noting that individual behavior can also be shaped by previous experience). When the probability of prey encounter is high (or the individual was successful in the past), associated with consistent environmental conditions, the memory component of the bird's behavior is enhanced and consistency will increase. On the other hand, if the probability of prey encounter is low, either because of prey mobility or scarcity or because the individual's current assessment of its foraging environment indicates paucity of prey encounter compared to past experience, foraging behavior should become less consistent (Dingemanse et al. 2002; Stephens et al. 2007; Cook et al. 2013). Imperial cormorants breeding at the León point colony are exclusively bottom divers (Gómez Laich et al. 2012) that feed mainly on Cusk-eels (*Raneya brasiliensis*) (Malacalza et al. 1994; Harris et al. 2016). This benthic fish thrives in the stable environment generated each season by the northern Patagonia frontal system (Buratti 2008; Saraceno et al. this volume), generating a predictable and stable food source for Imperial cormorants and making it a suitable scenario to exhibit behavioral consistency of foraging behaviors and areas used by birds over time. Dietary specialization has been linked to consistency in aspects of behavior, such as consistent location or depth of intensively used areas, as individuals fine-tune their behavior to target a particular type of prey (Elliott et al. 2009). A pattern of high consistency would be expected given a patchy spatial distribution of Cusk-eels that, however, remains stable over time.

Across seasons, Imperial cormorants mainly foraged on waters characterized by minimal power requirements compared with other areas in the available marine landscape (Fig. 7), capitalizing on the advantages of foraging in less energy-demanding areas, as expected in the hypothetical energy landscape scenario described by Wilson et al. (2012). The consistency found in the use of low energy-demanding marine landscapes for more than a decade reinforces the idea that the foraging ecology of Imperial cormorants from León point is based in a stable and predictable food source. Finally, successive records of the density of dives at different levels of landscape-dependent energy expenditure across seasons should help to inform us where animals allocate their energy and enable us to link this with potential or real environmental changes (e.g., climate or other global changes), something that should find particular resonance in conservation science.

Breeding Parameter Consistency The idea of long-term environmental stability around the colony is also supported by the high consistency of all breeding parameters recorded over time (clutch size, laying date, and breeding success, Fig. 9). The few anomalies reported in the foraging performance for particular seasons (see above) seem to underpin the idea of some degree of behavior plasticity in the species and the capacity of adult breeders to cope with potential low magnitude environmental changes. This capacity has been reported in other diving seabird species (Wilson et al. 2005; Miller et al. 2009; Dehnhard et al. 2016).

In general, global data have shown that Pelecaniformes and Suliformes (cormorants, gannets, and boobies) vary substantially among years in the timing of breeding, suggesting that these species may adjust egg laying in relation to some aspect of the local environment (weather, oceanographic conditions, and/or food availability) in the lead-up to the breeding season (Dawson 2008). However, our long-term records of laying date of the Imperial Cormorant suggest a low phenological sensitivity (i.e., phenological change over time). Although difficult to assert, the high consistency in time of breeding of Imperial cormorants at the study area can be consequence, at least partially, of a non-changing environment in the vicinity of the colony. Beyond that, the strong stability of clutch size across seasons may also indicate the environmental stability for the species during the winter or at least during the pre-laying period.

Although infrequent, delay/advance dates of 10 days in laying were recorded in 2005 and 2010 breeding seasons though. Among the local environmental drivers of phenology that have been identified, SST is widely reported to correlate with the distribution, abundance, and phenology of both local and migratory prey populations (Cheung et al. 2013). Unfortunately, we were unable to record in situ measurements of such physical variables during our study period, and satellite images of coastal sea surface temperature are not reliable enough to consider a correlational analysis.

A particularly low breeding success was reported during 2016. This anomaly was a consequence of a massive chick mortality event, apparently as an effect of an intense heat wave during the brooding period (Quintana et al. unpub. data). This kind of information results from long-term breeding data concomitant with environmental data continuously recorded over time and can be an important alert of a potential future constraint (under climatic warming scenarios, see Pessacg et al., this volume) on breeding activity, possibly leading to reduced reproductive output of this and other seabird species along coastal Patagonia Argentina.

Conclusion

In summary, the relative consistency of all biotic variables studied over time indicates predictable and stable environmental conditions in the surroundings of León point. However, if unexpected changes in the environment force individuals from this population to change foraging locations, or even develop new search strategies in order to be successful, they may not have the behavioral plasticity required to adapt to the new scenario, as this behavioral response may have been relaxed under long-term environmental stability. Potential inflexibility in breeding phenology in relation to temperature, for example, may leave Imperial cormorants vulnerable to trophic mismatch arising from shifts in timing of their prey. It is therefore interesting to continue to monitor this population over time in order to assess the extent to which behavioral consistency is maintained in the future and, in addition, to monitor other breeding colonies of this species to determine whether behavioral consistency is generalized in this species or is enabled by the prey system and environmental stability surrounding León point.

Finally, our long-term initiative is still in its infancy, and the datasets are still of insufficient duration to link them with inter-decadal variability from both natural and human-induced global change effects. However, they show definitively that a long-term approach, even in times of financial limitations, is possible and highlights the urgent need to maintain and possibly enhance existing long-term research and monitoring programs for this, and other, seabird species along coastal Patagonia.

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Long-Term Population Trends of Patagonian Marine Mammals and Their Ecosystem Interactions in the Context of Climate Change

Enrique Alberto Crespo

Species Assemblage

Marine mammals that live in the Patagonian shelf include several species of pinnipeds and cetaceans, most of which extend their distribution ranges to tropical or subtropical seas, through subantarctic waters, or beyond the shelf in deep ocean waters, all of them in the Southwestern Atlantic (SWA) ocean. The pinnipeds include the South American sea lion *Otaria flavescens*, the South American fur seal *Arctocephalus australis*, and the southern elephant seal *Mirounga leonina*, which live, feed, and breed in local populations in the Argentine sea or are part of larger distribution ranges (Crespo et al. 2007). Antarctic seals (crabeater *Lobodon carcinophagus*, Weddell *Leptonychotes weddellii*, and leopard seal *Hydrurga leptonyx*) and Antarctic *Arctocephalus gazelle* and subantarctic *Arctocephalus tropicalis* fur seals pass through the Argentine sea as erratic individuals (Crespo 2009).

Among cetaceans there are few species that use Patagonian waters for feeding and breeding, like the southern right whale *Eubalaena australis* and several species of small cetaceans like the dusky dolphin *Lagenorhynchus obscurus*, Peale's dolphin *Lagenorhynchus australis*, the common dolphin *Delphinus delphis*, the bottlenose dolphin *Tursiops truncatus*, and Commerson's dolphin *Cephalorhynchus commersonii* (Crespo et al. 2007). Like pinnipeds, some other cetaceans have wide or cosmopolitan distribution ranges but have local populations in Patagonian waters, i.e., the killer whale *Orcinus orca*, the pilot whale *Globicephala melas*, the false killer whale *Pseudorca crassidens*, the Risso's dolphin *Grampus griseus*, and several species of ziphiids very poorly known (Crespo et al. 2007, 2009). Eventually erratic

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individuals of hourglass dolphins *Lagenorhynchus cruciger* or Fraser's dolphins *Lagenodelphis hosei* may also appear in Patagonian waters.

The species' assemblage of top predators is completed with a number of species of marine birds, sharks, and rays that use the same prey species of fish and squid as marine mammals. Nevertheless, they will not be treated in the present chapter.

Ecological Characteristics of Marine Mammals

In most cases, marine mammals are close to the top of their food webs. They are considered to be K-strategists (Estes 1979; McLaren and Smith 1985). Their characteristics include large body size, long life spans, low reproductive rates, parental care, delayed reproduction, juvenile survival less predictable than that of the adults, and predictable adult survival. In some cases, they appear to show density-dependent responses in their population parameters (Fowler 1981, 1984; Doidge et al. 1984; Evans and Stirling 2001; Crespo et al. 2019). Some of these parameters for the cetaceans are tabulated by Lockyer (1984) and by Evans (1987). Among the mammals, they can be placed at one of the extremes of the r-K continuum; and at the other end, we find rodents and insectivores.

Marine mammals are long-lived species, with life span ranging from around 20 years for small dolphins and sea lions to 40–60 years in many species of seals, large delphinids, and whales. Females may produce at most a calf per year in species like seals, sea lions, otters, and cetaceans (Estes 1979; Riedman 1990). However, lower reproductive rates are found in the larger dolphins and whales, which may reach a calf every several years (Evans 1987). The breeding cycle in the southern right whale lasts between 3 and 4 years (Payne 1986; Payne et al. 1990*)*. Adult size and weight may range from 1 m and 15 kg in the sea otter *Enhydra lutris* to 30 m and 100 MT in the blue whale *Balaenoptera musculus*. Sexual maturity is usually delayed in life. Most of the seals and sea lions, and several species of small cetaceans, attain sexual maturity 4 to 6 years after birth. Some larger delphinids and ziphiids begin to reproduce after 9 years or more (Lockyer 1984; Perrin and Reilly 1984).

Parental care includes long periods of lactation and teaching of swimming and techniques for prey capture. In many large odontocetes, calves remain in herds close to relatives for several years. Seals, on the other hand, have a shorter period of parental care, with the hooded *Cystophora cristata* and elephant seals *Mirounga* spp., at one extreme, having a period of care of less than 1 month, which is in part offset by the high rates of energy transfer between mother and calf during lactation (Riedman 1990).

Survival is relatively uncertain between weaning and sexual maturity. This period, while the individual is learning different feeding and reproductive behaviors, is usually critical, and mortality is frequently due to lack of experience. However, once the basic skills are mastered, life becomes more predictable (Caughley 1966; Barlow and Boveng 1991). Population parameters, such as age at sexual maturity and reproductive rates, seem to be density dependent, but there is still some ongoing controversy on the subject (Eberhardt 1977; Fowler 1981; 1984; DeMaster 1984; McLaren and Smith 1985).

Many species, such as large whales, otters, and some sea lions, have been driven to the edge of extinction. Many of them have recovered or seem to be recovering. In some baleen whales, the response to the reduction in negative impacts has been quick (Best 1993), but for others it has been argued that interspecific competition may slow down the process (see discussion in Clapham and Brownell 1996). This leaves open questions concerning the existence of density dependence and the role that other environmental factors may play in that recovery. The lesson, from an ecosystem management point of view, is that even resilient ecosystems may take decades to return to their previous conditions after major disturbances and that there is no certainty that they will return to the same conditions. It is possible to eliminate or mitigate negative impacts on an ecosystem, but it is not possible to predict the trajectory of the response or its endpoint.

The Use of Aquatic Mammals by Humans

Humans have utilized aquatic mammals since prehistoric times, and archaeological records indicate the existence of tools and weapons made out of bone or stone for the apparent purpose of hunting mammals. In the cold regions of the planet, the scarcity of animal protein of terrestrial origin, and of alternative food sources, led humans to exploit marine mammals on the coast or at sea (Bonner 1982). There were several characteristics that made marine mammals a very valuable resource. They (a) had a large amount of fat and protein, more concentrated than in fish or shellfish, thus providing a high-value diet; (b) were a source of fur and leather that served for covering in cold and humid environments; (c) were accessible to humans with a simple technology; (d) were predictable in their locations or in seasonal migrations; and (e) in the case of pinnipeds, were easy to catch because of their vulnerability on land or ice (Crespo and Hall 2001).

Some of these characteristics were of particular advantage with the pinnipeds or coastal small cetaceans, which are sufficiently large to provide an ample reward without serious problems or risks in hunting them (Bonner 1982). Since Paleolithic days, the hunting of seals and sea lions was a matter of survival and an activity of vital interest for many coast-dwelling communities in northern and southern Europe, Asia, South America, and other parts of the world. In some cases, the contribution of the aquatic mammals to the energy intake of some of these communities was very large. In aboriginal populations of southern South America, more than 90% of the total energy intake was provided by fur seals and small cetaceans (Orquera and Piana 1987; Piana 1984; Schiavini 1990).

A harpoon with a detachable head was developed and used in the Arctic and in southern South America (Fig. 1a, b) (Orquera and Piana 1987), developed and used by subarctic and subantarctic nomad aboriginal people. The head, made of hard

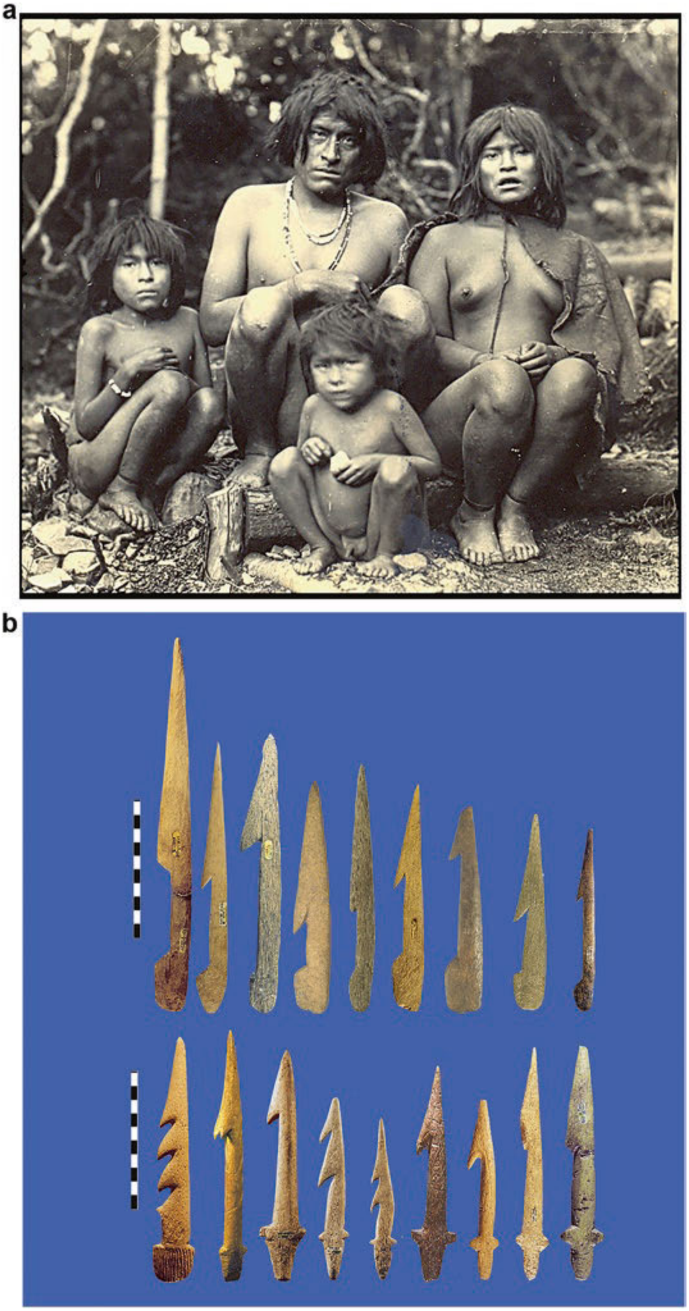

Fig. 1 (**a**) The photo of the Yamana family was taken by the *Mission Scientifique du Cape Horn* in 1881. (**b**) The harpoon line above are single shoulder base spearheads, typical of the last 3,000 years and in operation until the end of the nineteenth century. The bottom line are cruciform-based harpoon points, dated from about 7,000 to 5,000 years ago. (Scale in cm) (Courtesy of Luis A. Orquera and Ernesto L. Piana)

bone or ivory, was connected to a long stick. When the animal was harpooned, the head separated from the stick, but remained joined to a line and, in the case of the Inuit, to a float (avutang). The animal bled to death in the water and was eventually retrieved by means of the line and float. The harpoons varied from single sticks, with stone knives at the tip, to complicated technologies in the Inuit culture, but they all followed the same basic principles (Bonner 1982).

The economies of the sea-adapted people were extremely dependent on seal, sea lion, or cetacean products that were hunted or found stranded. The blubber was eaten, and, in areas with low access to wood, it was the main source of energy for cooking and used as fuel for lamps. According to Bonner (1982), the Inuit could have survived without the heat of the blubber lamps, but not without their light during the long Arctic nights. Prior to European colonization, subsistence hunting with a variable degree of intensity occurred along the entire Southwestern Atlantic coast (Orquera and Piana 1999; Gómez Otero 2007; Castilho and Simões-Lopes 2008; Bayón and Politis 2014; Borella 2014). This hunting pressure was considered low given past population abundance (Schiavini 1992; Orquera and Piana 1999; Zangrando et al. 2014). Fur seals were more frequent in archaeological sites than sea lions, possibly because of their availability in the environment. However, no record exists of the extent or rate of this harvest.

Whaling and Sealing in Modern Societies

The history of whaling as an industrial activity is much more recent (Evans 1987), although it remained a subsistence harvest for several centuries in the coasts of Japan, e.g., Baird's beaked whale *Berardius bairdii* fishery along the Sanriku and Hokkaido coast (Nishiwaki and Oguro 1971). The earliest recorded European whaling was carried out by Norse and Basque people in northwestern Europe and Spain, respectively. Norsemen caught whales off the coast of Tromsø as early as the ninth or tenth century, whereas the first data on whaling by Basque whalers dates from the year 670 in the Bay of Biscay. From there whaling spread to the rest of Europe, Greenland, and North America. At that time, during the sixteenth and seventeenth centuries, whaling became a major commercial operation quite different from subsistence activities. Northern right whales *Eubalaena glacialis*, bowhead *Balaena mysticetus*, and Atlantic gray whales *Eschrichtius robustus* were the main targets at that time and the first stocks to be depleted (Fig. 2). The Atlantic gray whale was soon driven to extinction (Allen 1980).

During the eighteenth century, whaling became established as an industrial activity and spread through the eastest coast of North America, the Indian and the Pacific oceans, and the subantarctic islands of the southern ocean. During this period, whaling was done using hand harpoons and rowboats, and the whales were processed alongside the boats. At this time, the Industrial Revolution resulted in a shift from a subsistence harvest to one based on monetary gain. The technological innovations brought about in those years, and the growing capital investment, resulted in more

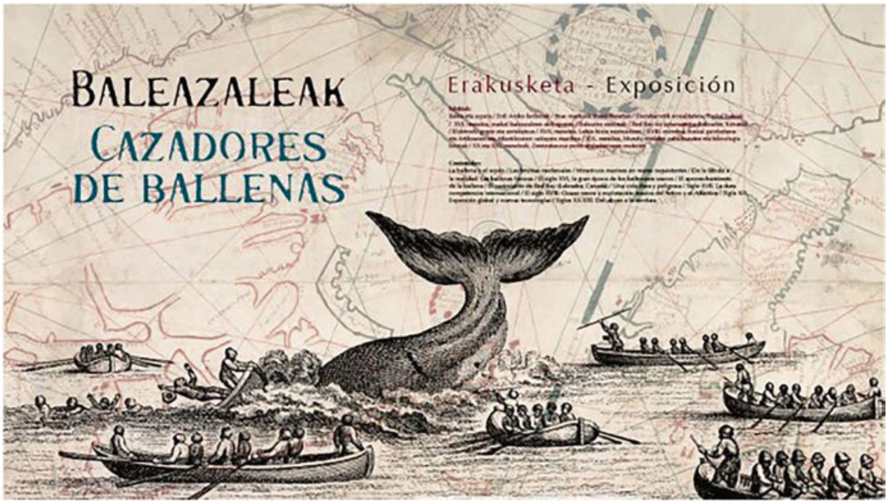

Fig. 2 Basque whalers catching a whale. (https://itsasmuseoa.eus/es/exposiciones/pasadas/40-baleazaleak-cazadores-de-ballenas)

efficient ways of hunting that led to the decline of several stocks. Right whales, fur seals, and sea otters, among others, started to decline during that period. Large rorquals and other species followed them later.

Modern whaling started at the end of the nineteenth century when the harpoon gun and the explosive harpoon were introduced and mounted on steam-driven vessels (Allen 1980). Fast-swimming whales like the rorquals, which were too fast for the rowboats, could now be taken with the new technology. This kind of whaling, with relatively minor changes, has also been used in the limited exploitation that took place until recent years.

Increasing demand and conceptual errors in terms of management, together with an intense competition for the resource, resulted in substantial declines in many marine mammal stocks. The history of whale catches shows that each target species was replaced by another one as the exploited stock was being depleted (Allen 1980; Evans 1987; Crespo and Hall 2001). The impacts of these harvests were probably very intense in some ecosystems, such as the Antarctic ocean, but they also affected other ecosystems visited by the whales during their migrations.

The long migrations of some aquatic mammals and other highly migratory species raise the issue of the ecosystem boundaries. Crespo and Hall (2001) wondered whether the management schemes for all ecosystems crossed by a major migration could be harmonized with respect to the migrating species and its impacts in each region's prey and competitors. Or should the definition of ecosystem, and therefore its management boundaries, be extended to include the whole migratory cycle? Practical reasons will probably decide the issue toward the first approach, but achieving harmony for all regions involved will not be easy, given the differences in priorities, economic standards, etc. The forum for this process may be, in the first stage, a combination of regional or national organizations when they exist and international bodies such as the International Whaling Commission – IWC (Crespo and Hall 2001).

Regarding sealing, it should be noted that, due to technological advances incorporated into the culture of aboriginal people, like fire guns, the original predator-prey relationship has been unbalanced over the last century. The possession of high-powered rifles and the ability to kill seals from a distance not only increased the number of animals hunted but also the rate of lost animals (i.e., wounded animals that were not recovered) (Bonner 1982). Smith (1987) estimated in 0.2% the annual ring seal lost by sinking in the harvest in the Canadian Northwest territories.

In the extreme South of America, in Tierra del Fuego, other human populations also sustained their economy based on pinnipeds. The channels and islands with a cold, wooded, and rainy environment were occupied until the last century by the Yámana, Halakwúlup (or Alacalufes), and Chono ethnic groups who, by their way of life, are collectively named as Canoe Indians (Orquera et al. 1979; Orquera and Piana 1983, 1984; Piana 1984).

The predecessors of these groups as early as 6000 B.P. were characterized by the intensive consumption of fur seals and sea lions (mainly the former and to a lesser extent the latter) and with less importance guanacos, birds, fish, and shellfish (Orquera et al. 1979; Orquera and Piana 1983, 1984; Piana 1984). A specimen of fur seal, due to its high caloric content, necessary to face the difficult climatic conditions in the area, would have provided around 200,000 calories, enough food for a group of 15 people for 3 days (Piana 1984).

In Patagonia, commercial exploitation started in 1790 when the Spanish Government created the Real Compañía Marítima establishing a whaling post at Puerto Deseado. That action was motivated by the fact that other European countries were pirating the resources in Patagonia. At least 16 right whales were taken during the first season, together with an undetermined number of sea lions and fur seals (Fig. 3). Nevertheless, the activity could not be sustained and whaling was abandoned soon, but the exploitation of pinnipeds spared and continued up to the end of the nineteenth century. Soon after the first Spanish expeditions, whalers and sealers of other nationalities, mostly British and American, started operating in the area. The peak of activity, particularly for whaling, peaked between 1820 and 1870. Sealers concentrated their activities in the Malvinas islands and Staten island. The rookeries located further north remained little affected or untouched. Because of its high-quality fur, the South American fur seal was the main target, although the South American sea lion and the elephant seal were also exploited for low-quality skins and oil (Bonner 1982).

In any case, from the eighteenth century on, an indiscriminate hunt for seals and whales began in the Southern Hemisphere. The southern fur seals were decimated together with the great whales, some of them reaching almost the brink of extinction, such as the Juan Fernández fur seal *Arctocephalus philippi* from the Juan Fernández islands, and the Antarctic fur seal from the South Georgia islands, where it was estimated that no less than 1,200,000 furs were extracted (Weddell 1825;

Fig. 3 Spanish soldiers killing sea lions. (https://fineartamerica.com/featured/spanish-soldiers-killing-sea-lions-the-gettyscience-photo-library.html)

Godoy 1963). Between South Georgia islands and Desolación island, 200 to 300 sailors and more than 2,000 tons of cargo moved by ships per year were occupied for the purpose of trade (Weddell 1825). A total of 320,000 sea lions and fur seals (and elephant seals that yielded 940 tons of oil) were hunted in the South Georgia islands alone between 1821 and 1822. According to Weddell, no less than 20,000 tons of elephant seal oil were transported to the markets of London since the islands were discovered to the date of his report.

The islands of the South Atlantic, as well as the coasts of Patagonia and Tierra del Fuego, with their numerous pinniped colonies, suffered attacks from whalers and sealers that entered the Argentine jurisdictional waters in search of skins, hides, and oil from these mammals during the last century (Godoy 1963), although this situation is prior to the May Revolution of 1810. According to the information provided by Spanish navigators in the period 1787–1791, there were many foreign ships that fished and hunted whales, fur seals, and sea lions on the Patagonian coasts (Ratto 1931). According to this last author, 14 ships were found in 1787, more than 30 in 1789, seven in 1790, and nine in 1791, all of them under the English, French, and North American flags. In addition to whaling, they landed to hunt sea lions, which was a clear territorial violation of the viceroyalty rights of that time.

A few examples of the Southwestern Atlantic that may be summarized will illustrate the situation here: the southern right whale, the South American sea lion, and the South American fur seal.

The southern right whale was one of the species of baleen whale that has been exploited for a long period in the "Brazilian Banks," the name given to the Southwestern Atlantic hunting area by the whalers. The first whales were taken around 1602 (Peterson 1948). By means of an extensive review of different bibliographical sources, the catch history of whaling for this species was reconstructed for the period 1670–1973. The model population trajectory indicates that the pre-exploitation abundance was around 30,000 to 35,000 whales (Fig. 4) (Romero et al. 2021). The abundance dropped to its lowest abundance levels in the 1830s when less than 1,000 individuals were left along the western South Atlantic ocean. Today, the current population abundance in that area is estimated to be around 5,000 whales (Cooke et al. 2015; Crespo et al. 2019), suggesting that the southern right whale population remains small relative to its pre-exploitation abundance (recovery level, 10–15%). During the 1960s and in spite that the species was protected nationally and internationally, 3,000 whales were taken in the Southern Hemisphere by illegal Soviet pelagic whaling operations, delaying the recovery of the species. Of those,

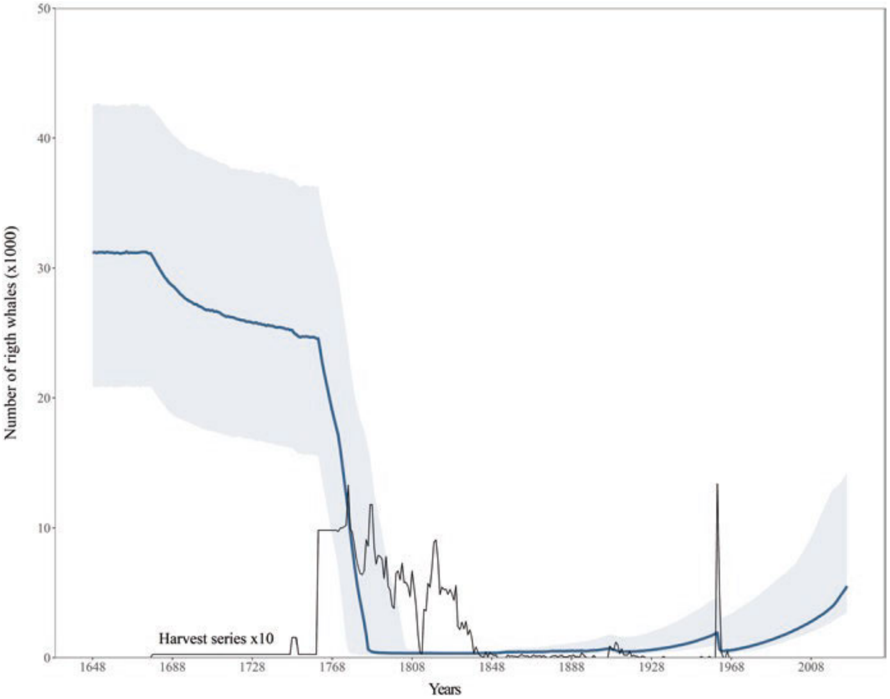

Fig. 4 Population trajectory of southern right whales in the Brazilian banks (blue line) and time series of catches (black line). The shaded areas correspond to the first and third quartiles. (After Romero et al. Subm.)

the number taken off Argentine waters was 1,356 and mainly during the 1961/1962 season (Tormosov et al. 1998). The results of the population dynamic modeling provide insights into the severity of whaling operation in the South seas and how the population responded at low densities and thus contribute to understanding the observed differences in population trends across the global distributional range of the species (Romero et al. 2021).

The South American sea lion is the most conspicuous marine mammal along the South American coasts, both Atlantic and Pacific, where it was heavily exploited. As a consequence of this exploitation, many of its colonies in the Argentine sea were decimated during the early twentieth century and nowadays show a clear recovery. As a K-strategist subject to exploitation, this population dropped to very low levels. After protection was imposed, recovery was at first very slow. After 50 years from hunting cessation, the population still represents only 35% of its pre-exploitation abundance (Fig. 5) (Romero et al. 2017). However, the opportunistic and plastic behavior of the South American sea lion, together with a high level of juvenile survival, resulted in a faster rate of population recovery in recent decades. Possible reasons for this improved survivorship may include an increase in the availability of food resources, prey switching, and a decrease in other causes of mortality (Romero et al. 2017). It was particularly interesting to understand how the population responded at low densities, how human-induced mortality interplays

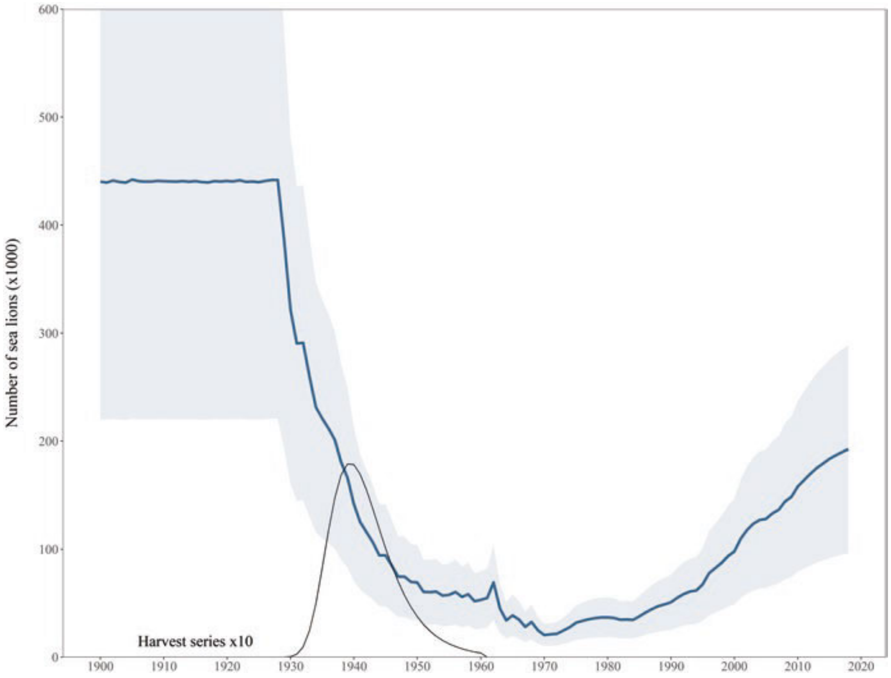

Fig. 5 Population trajectory of South American sea lions (blue line) and harvest series (black line). Shaded area indicates ± SD (after Romero et al. 2017)

with natural mechanisms, and how density dependence may regulate population growth. The population trajectory shows a nonlinear relationship with density, recovering with a maximum increase rate of 6%. Considering that the population of sea lions from this region holds around 72% of the species abundance within the Atlantic ocean, the population dynamic modeling provides insights into the potential mechanisms regulating the dynamics of South American sea lion populations across the global distributional range of the species.

The South American fur seal was heavily exploited from the nineteenth century until the end of the twentieth century throughout the South Atlantic coast, from Uruguay to Tierra del Fuego, the Malvinas islands, and Staten island, mainly for its skin and oil. In Uruguay, private concessions, and, later, the Uruguayan state killed at least 800,000 individuals between 1893 and 1991 (Franco-Trecu et al. 2019, and references therein). The exploitation in Uruguay lasted until 1991, while in Argentine waters the fur seal almost disappeared where 100,000 animals were taken in north and central Patagonia. These figures may include sea lions as well; nevertheless, they may be largely underestimated. The harvest closure in Uruguay probably led to a population increase that allowed to recover and repopulate the South Atlantic again. The rate of increase is currently around 8% per year, and several individuals tagged in Uruguay have been resighted in Patagonian waters (Crespo et al. 2015). Therefore, the Uruguayan fur seal population may not only be the largest of this species, but also helps to sustain the rapid growth of fur seals in the Argentine sea (Franco-Trecu et al. 2019).

The understanding of the underlying processes and comprehensive history of population growth after a harvest-driven depletion is necessary to assess the long-term effectiveness of management and conservation strategies.

A Change in Problems: Incidental Mortality and Competition for Resources Instead of Direct Catches

During the 1960s a major change started in the interactions between marine mammals and humans, a change that lasted for two decades at least. Almost at the same time that the direct catch of large whales was going down and the IWC promoted the moratorium for direct takes, incidental catch appeared as a huge problem with the development of many types of fisheries all around the world including gillnets, trawls, purse seiners, and longlines (Crespo et al. 1997; Crespo and Hall 2001). However, the interaction and the intensity was not the same with each type of gear. Perhaps the bigger problem arose with coastal species and gillnets, which mainly affected small cetaceans especially when the Food and Agriculture Organization (FAO) promoted the use of that fishing gear all around the World in less developed countries as a way to alleviate hunger. Nevertheless, the interaction with other gears like trawls should not be underestimated given the huge fishing effort and biomass extraction.

In northern Patagonia, as well as in waters of Buenos Aires province, Brazil, and Uruguay, gillnets became the most dangerous gear especially for the Franciscana dolphin *Pontoporia blainvillei*, a species which is thought to be in real danger given the high rate of incidental catch. The mortality of Franciscana in gillnets, mostly of juvenile individuals, is the most serious problem for the species throughout its distribution range, probably since the end of World War II (Fig. 6a, b). At that time, many artisanal fisheries for sharks developed from Rio Grande do Sul to Patagonia for vitamin A production, which was exported to Europe. Nevertheless, minimum mortality rates were always estimated around several thousands of individuals throughout the distribution range. Nowadays in Argentine waters, no less than 500 dolphins per year are taken (Crespo 2009). The estimated mortality for the whole distribution range could be around 1,200–1,800 individuals per year (Reeves et al. 2003).

Due to the variability found in mortality rates and abundance estimates, it is not known whether those mortality rates are sustainable (Crespo et al. 2010). In rough numbers, the upper limits of abundance estimations cannot account for the lowest estimates of mortality. Therefore, more precise estimates are needed along with conservation measures to preserve the species. Population viability analysis using data on abundance, bycatch, and population growth suggested that levels of bycatch were not sustainable in all Franciscana Management Areas (FMAs) in the early 2000s. These analyses led to the classification of the Franciscana as Vulnerable in the International Union for Conservation of Nature (IUCN) Red List (Zerbini et al. 2017). Abundance estimates obtained in the late 2000s showed a similar pattern, with bycatch levels ranging from 3% to 6% of the population size in all FMAs for which information is available. Other threats to the Franciscana include habitat degradation (Crespo 2018). A large proportion of the distribution range is subject to pollution from several sources, especially the agricultural use of land and heavy industries between São Paulo in Brazil, La Plata river, and Bahía Blanca estuary in Argentina. The coastal zone is also intensely used for boat traffic, tourism, and artisanal and industrial fishing operations (Crespo 2018).

In Patagonia, the biggest fishing effort since the 1980s was carried out with midwater and bottom trawl nets. There is no use of gillnets with the exception of Tierra del Fuego. The problem with trawls along the Patagonian coast is different in nature: in gillnets, cetaceans get trapped; in trawl nets, the animals enter in the net for taking fish or squid. For the first time incidental catch rates of marine mammals in trawl nets were estimated during the 1990s (Crespo et al. 1997). Working with fishing captains and officers allowed to estimate mortality rates. The species caught were South American sea lions, dusky dolphins, Commerson's dolphins, and common dolphins (Fig. 7). Other species were also recorded, i.e., South American fur seals and Peale's dolphins, but reported deaths for these species were infrequent.

Since the development of the hake *Merluccius hubbsi* trawling fishery in Patagonia, during the 1970s, sea lions have drowned in nets. The opportunistic behavior of taking advantage of new sources of food makes this species vulnerable. Sea lions interact with all types of fisheries, but are not killed in all of them (Crespo et al. 1994, 1997, 2007, 2012). They take the bait or fish caught in longlines and

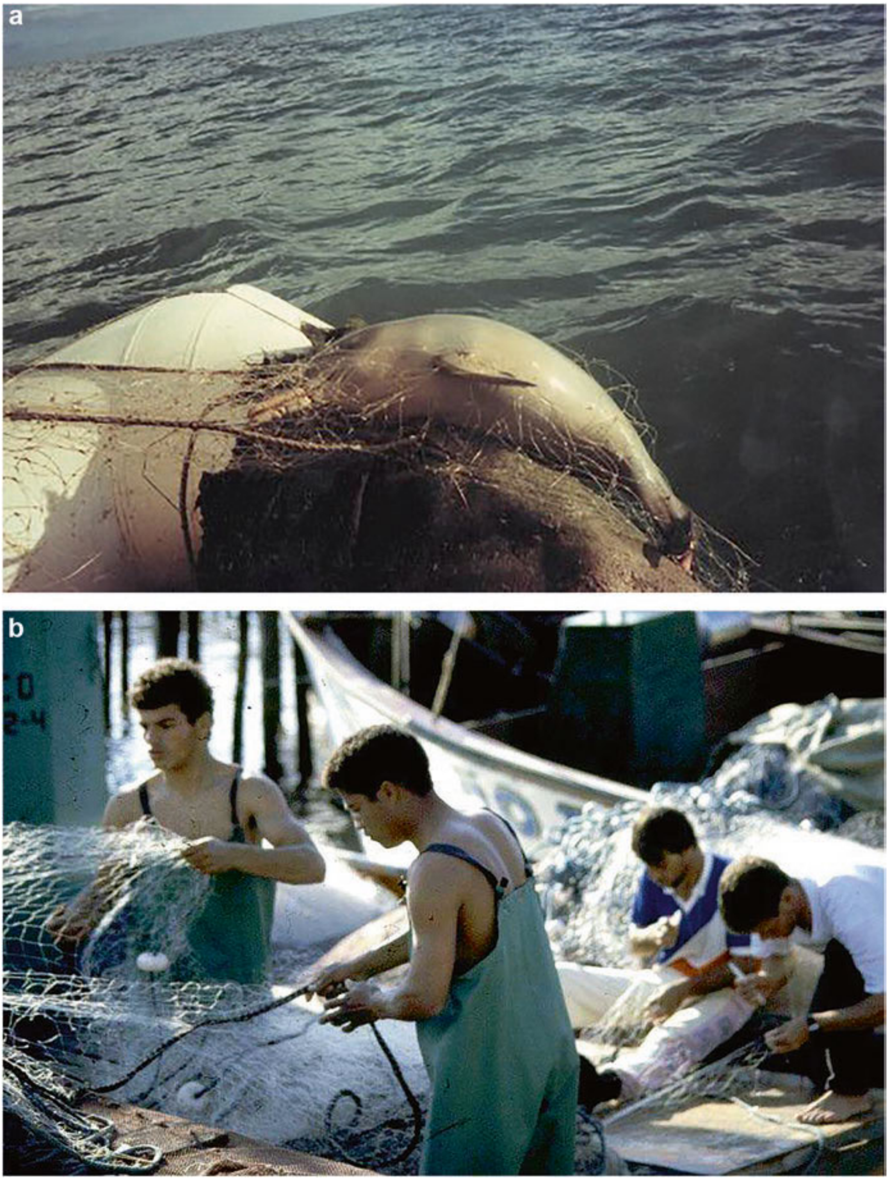

Fig. 6 (**a**) Franciscana dolphin entangled in coastal gillnets in Buenos Aires province (courtesy of Pablo Bordino), (**b**) fishermen in Rio Grande do Sul, Brazil (Courtesy of Eduardo R. Secchi)

gillnets, but are rarely caught in these gears. In Patagonian hake and shrimp *Pleoticus muelleri* trawls, mortality is roughly estimated between 1% and 2% of population size, which is today absorbed by a higher rate of increase, around 5.6%. Sea lion populations are still increasing and have not yet reached carrying capacity. Given

Fig. 7 Commerson's dolphins caught in mid-water trawls in Patagonian waters (photo Marine Mammal Laboratory CENPAT-CONICET)

the huge amount of biomass taken by the trawling and jigging fisheries, in which the main targets are also prey of sea lions, the carrying capacity in the next future may be very much lower than the original one. South American sea lions showed the lowest catch rates, but they were caught in seven of the nine types of the trawl fishery.

The mid-water trawl for shrimp showed the highest mortality rates for all the species. Between the 1970s and the 1990s, the negative effect on dusky dolphins was very severe given that the maturing females were the age and sex class mostly affected (Dans et al. 1997). In the following years, the fishing effort for shrimp and dolphin mortality decreased. Although mid-water trawls were forbidden for fishing shrimp in the mid-1990s, several experimental and commercial hauls were performed with this net to catch Argentine anchovies. Each time that one of these hauls was done, dusky and/or common dolphins were found entangled (Crespo et al. 2000). Eight events of dolphin mortality in mid-water fishing for anchovies were recorded during the 1990s in the Argentine sea. Some of these records simply noted that entanglements occurred and precise information was gathered only for three events. The mouth of the net was around 40 m high and 40 m wide. The catch rates estimated in those fishing operations reached almost nine individuals per day, per vessel, much higher than those calculated when fishing for shrimp. Several important features can be pointed out from the entanglement events in mid-water trawls: (1) the interaction was not passive, i.e., dolphins actively moved into the net; (2) entanglements seemed to be night-related; and (3) dolphin bycatches appeared to present a contagious distribution (Crespo et al. 2000)

Humans and Aquatic Mammals as Competitors

The direct exploitation of aquatic mammal resources for both primitive Paleolithic communities and modern societies can be considered as a predator-prey relationship from an ecological point of view. Since the mid-1960s, the exploitation of whales and other aquatic mammals has been questioned (Barstow 1990; Stroud 1996), and this has resulted in a stop of the direct exploitation of most of these populations. In the same period, however, a large increase in the extraction of biomass by the world's fisheries has resulted in other interactions between humans and aquatic mammals. A by-product of fisheries has been incidental mortality. However, in ecological terms, direct takes and incidental mortality in fishing gear are equivalent processes; animals die one way or the other. Species or areas may change but in essence show the same ecological events. At the same time these processes were going on, the fast development of technology increased the efficiency of fishers at a rate that the prey species cannot match (Crespo and Hall 2001). Because of this, management is needed to make a sustainable use of the resources based on science procedures that could allow for a cautionary management scheme.

The competition between aquatic mammals and humans has intensified to the point that today it is probably more significant than the direct exploitation of aquatic mammals (Crespo and Hall 2001). Competition and predation are key processes in the regulation of natural communities. In the particular case of interactions among top predators and fisheries, the competitive relationships have been a discussion point where culling proposals for the sake of fisheries are frequent topics (Yodzis 1994).

The concern often expressed over the quantities of fish consumed by seals, dolphins, and other marine mammals, and the possibility that they were affecting the size and availability of the fish stocks and thus the viability of fishing industries, led to demands made for culls to reduce the number of marine mammals. These thoughts stem from the belief that fewer marine mammals will consume less fish, which will leave more fish available for fisheries to catch, with resulting benefits for the fishing industry and the livelihood of fishers (Anonymous 1999). However, the scientific assessment of competitive interactions is not an easy task, considering the number of possible paths and the complexities of trophic links in the marine food web. Furthermore, long-term trends in the system can go in the opposite direction to short-term trends (Yodzis 1994). Experiences carried out in Canada, Great Britain, South Africa, and many other countries did not achieve the projected results in terms of a surplus of fish biomass after culling the respective populations of marine mammals (Bowen and Lidgard 2012).

In many cases, fisheries affect marine mammals by decreasing the abundance of their prey species. This problem has been well documented in Franciscanas. The interactions between the fishery operating in this region and the small cetaceans have been reviewed by Pinedo (1994) and Secchi et al. (1997). The principal prey of this coastal and river dolphin are the sciaenids, which have been severely depleted by coastal fisheries. Two studies conducted for the same area (Rio Grande do Sul) in 1982 and 1997 showed preliminary evidence of a shift in the diet of the Franciscana (Pinedo 1982; Bassoi 1997).

In Patagonia, the marine community is organized around the trophic system of three main target species: Argentine hake, Southern anchovy *Engraulis anchoita*, and Argentine shortfin squid *Illex argentinus* (Angelescu and Prenski 1987). At the same time, these species are key elements in the diet of most top predators and also are important fishery resources. Therefore, some of the basic conditions for competition are met if the species abundance decreases as a consequence of fishery extractions.

Koen Alonso (1999) studied the diet in several species of top predators including marine mammals and elasmobranchs. Figure 8 shows the proportion in the % index of relative importance (IRI%) of a few key and abundant prey species as part of the diet of South American sea lions, beaked skates *Zearaja flavirostris*, tope sharks *Galeorhinus galeus*, spiny dogfish *Squalus acanthias*, and dusky dolphins.

Sea lions show differences in diet with sex, and the skate and the dogfish show differences with sexual maturity using for feeding different parts of the water column (Koen Alonso 1999); therefore, they were treated as different trophic species. The bottom trawling fishery is included in Fig. 8. These and other top predators not considered here use the same prey species like hake and squids, as immature stages near the surface or mature stages close to the bottom.

At the end of the 1990s, it was estimated the food consumption by the South American sea lion population in northern and central Patagonia (Marine Mammal Laboratory unpub. information after Koen Alonso et al. 1999). The estimation was performed based on the individual daily intake and population size. In order to obtain mean daily intakes for males and females, the growth curves, age and sex

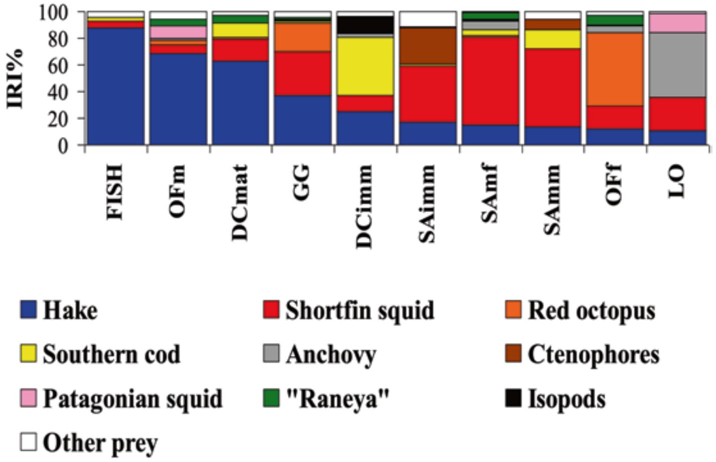

Fig. 8 Index of relative importance of prey of different top predators: OF *Otaria flavescens*, DC *Zearaja flavirostris*, GG *Galeorhinus galeus*, SA *Squalus acanthias*, LO *Lagenorhynchus obscurus*. m, male; f, female; im, immature; mat, mature (Marine Mammal Laboratory CENPAT-CONICET, unpubl.). FISH is trawling fishery

composition, and the rates of biomass ingestion equations for juveniles and adults of the Otariidae were used (Innes et al. 1987). The total population consumption was estimated on the basis of population size in 1996. The consumption by prey was obtained from the proportion in weight of each prey species in the diet and considering sex differences.

For the mid-1990s population of 67,800 sea lions, the total consumption was estimated in 148,000 metric tons, which include 72,000 tons for Argentine hake, 25,000 tons for the red octopus *Enteroctopus megalocyathus*, and 21,000 tons for the Argentine shortfin squid. Minor consumptions include 9,300 tons for the "raneya" *Raneya brasiliensis*, 4,300 tons for southern anchovy, 8,800 tons for the Patagonian squid *Doryteuthis gahi*, and 7,500 tons that correspond to 31 other prey species.

In the present day (late 2020s), the total number of sea lions in the Argentine sea, excluding the Malvinas islands, is around 130,000–135,000 individuals, twice of that in 1996 (Romero et al. 2017; Grandi et al. 2020). Therefore, the total consumption of prey may be twice as well. If the hake consumption by sea lions doubled, the take today is in the same order of magnitude of that of hake taken by the fishery, which reached around 270,000 tons in the last few years (Fig. 9). This means that this consumption should be considered in the management models for these species, at least for hake and shortfin squid.

The biomass extraction increased exponentially during the 1990s by means of an agreement with the European Union, reaching by 1997, 1.34 million tons considering all species caught. If the fishing discards are to be considered, the total extraction raises to 1.64 million tons (Fig. 9). At the late 1990s, the catches fell down, and after that they were sustained around 800,000 tons including 150,000 of fish

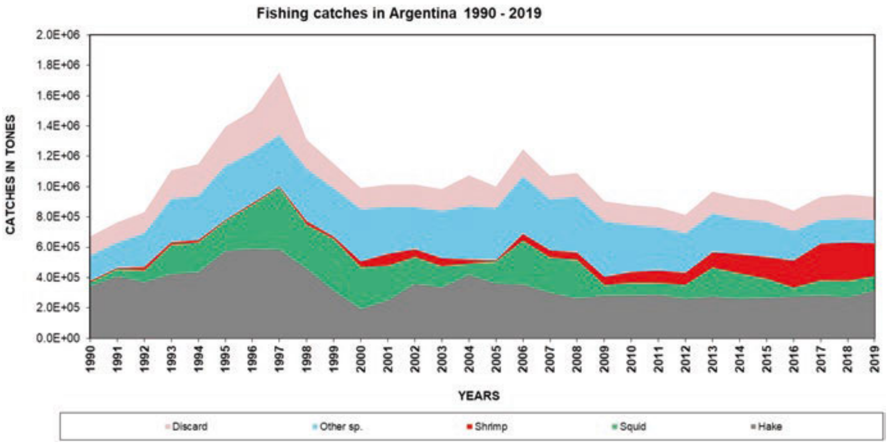

Fig. 9 Catches of target species of the trawling and jigging fisheries in Patagonia 1990–2018. (Data from Secretary of Fisheries and Aquaculture of Argentina and from the Marine Mammal Laboratory CENPAT-CONICET, unpubl.)

discards thrown back to the sea by the fishing vessels (Marine Mammal Laboratory unpub. information).

However, the structure of the food chain has changed; it is not the same as that 30 or 40 years ago when the trawling fishery grew exponentially. The relative abundance of the species in the community has changed as a consequence of the huge fishing extractions of biomass, but also by throwing thousands of tons of fish discards and wastes of the factory vessels back to sea and the mechanical action of the trawling nets at the bottom of the sea. This can be very easily seen in the changes in the diet of the beaked skate *Zearaja flavirostris*, which has been monitored for more than 30 years (Fig. 10). During the 1990s, the index of relative importance of common hake in the skate was around 50% of the biomass ingested. Thirty years after the IRI fell down to 10% with increases in other less nutritive species like the southern cod *Patagonotothen ramsayi* and hake heads and backbones found in the bottom of the sea thrown back to the sea by factory vessels (Koen Alonso 1999; Herrera 2011; Marine Mammal Laboratory unpub. information).

A recent analysis of Patagonian food webs across the past 7,000 years considered three top predators, sea lions, fur seals, and Magellanic penguins. Ancient food webs were shorter, more redundant, and overlapped more than current ones, both in northern-central and in southern Patagonia. This surprising result may be best explained by the huge impact of sealing on pinnipeds during the fur trade period, indicating that in modern food webs there has been a release from intraspecific competition and a shift toward larger and higher trophic-level prey (Saporiti et al. 2014). The three top predators overlapped more in the past. This, in turn, has led to longer and less overlapping food webs with fur seals and sea lions well below the original carrying capacity.

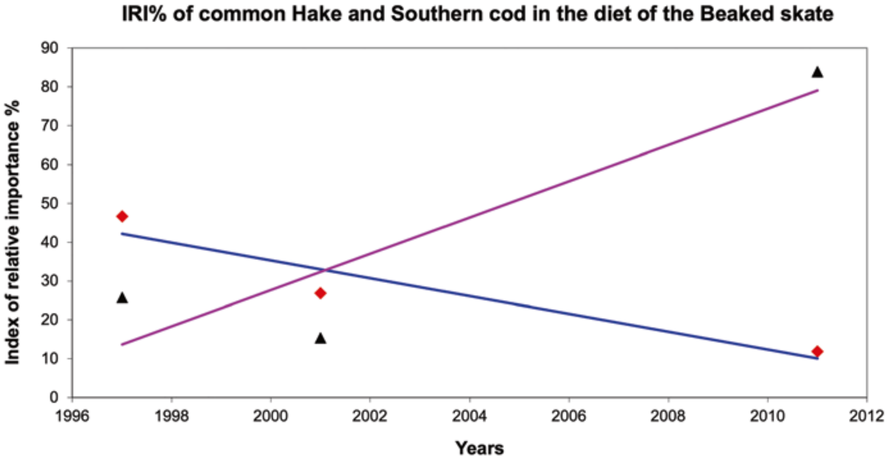

Fig. 10 Index of relative importance of two preys of the beaked skate in Patagonia (red diamond, common hake; black triangle, southern cod) (Marine Mammal Laboratory CENPAT-CONICET, unpubl.)

Economic Value of Marine Mammals: Substitution of Direct Takes by Ecotourism

With the moratorium on whale hunting and the changes in public attitude toward marine mammals, new economic activities have evolved in the last few decades, on the base of non-consumptive use of the species. Whale watching and ecotourism came to replace hunting and harvest and are now significant sources of benefits and employment in some areas of the world, mainly in western countries. However, uncontrolled whale watching and tourism can also have adverse impacts on the populations or the habitat. The IWC has started to consider this issue as another component of the management of the whale stocks (IWC 1997).

In Valdés peninsula whale watching started informally in 1973 and has been steadily increasing, based mainly on the observation of coastal wildlife. The southern right whale and the Magellanic penguins *Spheniscus magellanicus* are the main attractions, followed by the sea lions, the southern elephant seal, dusky, Commerson's, and common dolphins and other concentrations of nesting seabirds. It is clear, however, that the marine mammals of the area are the principal magnet for tourists. The number of tourists visiting Valdés peninsula has increased steadily in recent years, averaging 300,000 per year, while those watching whales is around one third (Anuario Estadístico de Turismo 2018–2019). The revenues in northern Patagonia to observe wildlife are close to U$S 100 million per year in direct benefits. It is impossible to predict today whether this industry will continue expanding for many years or if it will soon reach some kind of carrying capacity. By 2006, Argentina had the largest number of whale watchers in Latin America (Hoyt and Iñíguez 2008) and most of these came to Patagonia (Argentina).

In fact, very close to Valdés peninsula, the presence of whales in the northwest area of San Matías gulf within the San Antonio Bay Marine Protected Area (SABMPA) during winter and early spring has become frequent enough to set since 2012 an experimental program of whale-watching tourism. This planning was designed and implemented according to the current legal framework and enforced by the Environment and Sustainable Development Secretary (SAyDS) of the Río Negro province (Arias et al. 2018). Economic and educational benefits for the coastal communities are clearly positive aspects (Constantine and Baker 1997) and should provide adequate regulations in order to make the activity sustainable in the long term (Crespo and Hall 2001). However, in many places there is pressure from the private sector to open to tourism every attractive wildlife area along the coast and to allow the development of new activities, such as diving with dolphins, whales, and sea lions.

The other activities that produce significant economic benefits and employment in the region are fishing and oil exploitation. Both compete with ecotourism in the sense that, if it is well managed, ecotourism provides positive benefits to coastal communities while fisheries and oil activity may have negative ones. Overfishing of some of the target species, such as hake and squid, which are also important preys for many aquatic mammals and seabirds may produce decline of predators (Crespo et al. 1994, 1997; Koen Alonso et al. 1998, 2000), while oil exploitation and transport are important sources of pollution for wildlife and the marine environment at all levels (Geraci and St. Aubin 1990). Fisheries and oil activity as well as ecotourism provide employment for many people. Nevertheless, they have opposite actions one over the other. While the impacts of oil pollution on wildlife are sometimes very visible, the impacts of fishing (bycatch or unlimited biomass extraction) or tourism are less obvious to the public and are more difficult to trace to direct cause-effect mechanisms (Crespo and Hall 2001).

Marine Mammals and Climate Change

Aside from the problems for marine mammals that have been described in the previous sections, climate change has come to complicate the picture even more and make it less predictable. Marine mammals are usually considered as indicators of changes in their ocean environment. Despite being resilient animals, the rise of ocean temperature, acidification, and sea levels are just some consequences of climate change that may impact marine mammals in the near future, their food sources, and their habitats.

Although the effects of climate change on marine mammals are yet to be seen, it is clear that some species will be winners and others will be losers. In the case of the potential collapse of some populations, it may have therefore irreversible consequences for the ecosystem functioning and services (Albouy et al. 2020). Few cases of effects on populations have been documented in species living in SWA waters, mostly related to the Southern Ocean, which is connected to the SWA by water currents which, in turn, transport nutrients far north. Many species are connected to both areas by feeding and breeding, e.g., the southern right whale.

Klein et al. (2018) examined by means of ecosystem modeling how projected effects of ocean warming on the growth of Antarctic krill *Euphausia superba* might affect populations of krill and dependent predators (whales, penguins, seals, and fish) in the Scotia sea. The projected effects of ocean warming on krill biomass would be strongest in the northern Scotia sea, with a ≥40% decline in the mass of individual krill. These results may vary by location and species group. Klein et al. (2018) also stated that risk reductions at smaller spatial scales also differed from those at the regional level, which suggests that some predator populations may be more vulnerable than others to future changes in krill biomass. Their findings indicate the importance of identifying which species may be more vulnerable to negative effects of climate change and develop protection measures at different spatial scales, in order to avoid increasing risks with rising ocean temperatures.

Trathan et al. (2003) showed that the acoustic density of Antarctic krill at South Georgia is negatively related to temperature, with acoustic biomass reflecting variability in oceanographic conditions. They also showed that, over the past two decades, periods of high krill biomass have only occurred during anomalously cold periods and that the reduced levels of prey availability are linked with anomalously warm periods. If so, then low prey availability must affect the population processes of both gentoo penguins *Pygoscelis papua* and Antarctic fur seals. Long-term series of data showed that strong links exist between sea surface temperatures during the preceding winter period and fur seal breeding performance. For more than 20 years, positive anomalies in sea surface temperature in the tropical Pacific and at South Georgia explained significant nonlinear reductions in Antarctic fur seal pup production (Forcada et al. 2005). The same happened with gentoo penguins in years of lowest reproductive productivity for Antarctic fur seals (1990/1991, 1993/1994, 1997/1998, and 1999/2000) (Trathan et al. 2006).

The southern right whale is another krill eater that feeds in the waters around South Georgia and congregates to breed in the waters surrounding Valdés peninsula, Argentina (Leaper et al. 2006). Krill is the main prey at least for whales feeding to the south of 50° S as reported by Tormosov et al. (1998) based on stomachs of whales caught by the soviet fleet between 1951 and 1971. Whales taken north of 40° S were feeding on copepods. Between 40° and 50° S copepods dominated, but there were also euphausids in the sampled stomachs. Leaper et al. (2006) compared sea surface temperature (SST) time series from the SWA and the El Niño 4 region in the western Pacific to an index of annual calving success of the southern right whale breeding in Argentina. There they found a strong relationship between right whale calving output and SST anomalies at South Georgia in the autumn of the previous year and also with mean El Niño 4 SST anomalies delayed by 6 years. These results extend similar observations from other krill predators and show clear linkages between global climate signals and the biological processes affecting whale population dynamics. Seyboth et al. (2016) analyzed and concluded that the body condition and foraging success in the southern right whale might be affected by climatically driven change in the abundance of krill, the whales main prey on the feeding grounds. By means of cross-correlation analysis, they examined the response of the species to climate anomalies and krill densities and found that global climate indices influence southern right whale breeding success in southern Brazil by determining variation in krill availability for the species. Therefore, an increased frequency of years with reduced krill abundance, due to global warming, is likely to reduce the current rate of recovery of southern right whales from historical overexploitation.

Southern right whales were also subject to high mortality of calves in some particular years, namely, the seasons of 2008, 2009, and 2012. Many tissue samples were collected and analyzed, but no consistent lesions, pathologic processes, or elevated levels of algal biotoxins were identified that help explain these mortality events (Rowntree et al. 2013). Even that the mortality rate has been increasing since the early 1970s and it may be explained by a density dependence response (Crespo et al. 2019), the peaks of high mortality are not, and those particular years may be related to other temporal and spatial anomalies in the feeding areas that have not been detected yet.

With the exception of southern right whales, there is no evidence of climate change effects on marine mammal populations in Patagonian waters. In any case, these potential effects may be overlapped with other negative effects of anthropic origin such as fishery impact or pollution. What may then be expected? Marine mammals using beaches to rest or breed could be affected in habitat use if the sea level rises. This may be the case of the South American sea lion, which occupies more than 120 rookeries in the continental coast and islands. South American fur seals would be less affected since they live on rockier coasts. Furthermore, if the sea surface temperature rises, cryophilic species may also lose habitat.

It must be said that the recovery or loss of a given species sometimes does not depend on active policies. Many of them recovered only stopping the harvest or catches. Nevertheless, stopping the harvest or catches is not enough for a given species to recover, like in the northern right whale. The case of the vaquita *Phocoena sinus* is even worse; catches never stopped and still continued when the population was estimated to be under 20 individuals. In spite of the huge efforts and investment done in conservation, these species are going to be lost in the near future. The baiji *Lipotes vexillifer* was lost recently. Given the uncertainty of the future with climate change and all the variables playing a role is very little what humans may do to preserve the ecosystem in a reasonable shape.

What Should We Do with Marine Mammals?

There is a long debate around the utilization of marine mammals as a resource (Crespo and Hall 2001). The debate indeed revolves around two conflicting viewpoints. On the one hand, there are those who accept the utilization of marine mammals as a resource and defend their concerns on an adequate and cautious management, ensuring the sustainable use of populations in the long term. The IWC discussed policies on that basis (IWC 1994). On the other hand, there are those who do not accept the utilization of marine mammals as a resource, basing their views on a moral judgment that is strongly culture-dependent (Barstow 1990; Crespo and Hall 2001). In this case, there is no way to maintain an objective discussion. On the conservation side, there is also a need for objectivity in the sense that different situations or cases should be considered in the proper degree of importance. Otherwise, if every situation runs the same risk, for those officers that have to make management decisions, it is difficult to evaluate which alternative is the more important.

As can be seen, the interactions between aquatic mammals and humans are related, not only to ecology but also to ethics and economics. The interactions flow in many directions, and the solution for conservation and management of marine mammal populations lies in an integrated management in which all the stakeholders can define convenient courses of action that allow them to coexist. These parts should include the nations involved, fishermen, industry leaders, and environmentalists. Much of the success of conservation programs stems from the ability of the leaders of the different sectors to understand and communicate with each other and to find the common objectives that sometimes are lost in heated debates (Hall 1996, 1998).

Presently, most of the marine mammals, previously exploited or not, are recovering, some of them with high rates of increase. Sea lions increase at a rate of 5.6%, right whales at 2.2%, while from 2000 to 2007 they grew at 7%; fur seals are increasing at 8% (Crespo et al. 2015, 2019; Grandi et al. 2016). Sea lions and right whales are showing some evidence of density dependence. Sea lions seem to be reducing their bodies (Drago et al. 2010), and right whales are expanding from Valdés peninsula to deeper waters and San Matías gulf (Arias et al. 2018; Crespo et al. 2019). The only exception is the Franciscana for which the real effect of incidental mortality is unknown, whether it is sustainable or not. However, most of the species that were exploited in the past did not achieve yet the original population sizes. This is the case for the southern right whale, the sea lion, or the fur seal. For small cetaceans there is no previous information to which to refer original sizes or calculate rates of increase.

Possible Futures

The present chapter describes the history of the ecological relationships between a group of marine mammals and humans, the exploitation, and recovery of the most conspicuous top predators of the Southwestern Atlantic. It also attempts to explain the ecological mechanisms that allowed these species to recover. However, which are the potential scenarios that sea lions, fur seals, small cetaceans, and right whales may expect in an ecosystem in continuous change? None of them has reached yet a stable population size. However, they may and will reach one sooner or later and with high probability will be lower with regard to the original one. The huge amount of biomass extracted by the fishery will remain for decades. Therefore, in order to keep these and other top predator safe, there is a need of reaching an agreement of an equilibrium point in which the fishery catches may coexist with sustainable abundances of every one and all of the top predators in the ocean. This means to leave the necessary biomass to keep those populations safe. Nevertheless, the context of climate change in which these species are recovering may produce different results of those expected. Climate change is an uncertain threat to marine ecosystems and the services they provide and how it will affect the populations. Reducing fishing pressure is one option for mitigating the overall consequences for marine biota.

From an ecosystem point of view, the conservation and management of aquatic mammals require two very important things to consider: (a) mitigate the impacts of fishing gear and (b) deal with pollution and other forms of habitat degradation. It should also consider the coexistence of different forms of utilization *sensu* Hall (1996) following basic ecological principles avoiding the exploitation of some elements and protecting others and consider environmental variability in the short and long term and consider socioeconomic and cultural differences, including the development of an understanding and tolerance of those differences in all participants. Nowadays, management should be under international regulations, considering the different problems that need to be addressed. Global, regional, and local aspects of populations should be considered within a variety of alternative solutions, taking into account ecological, economic, "moral," cultural, and social variables (Hall 1996; Crespo and Hall 2001).

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Global Change Effects on Biological Interactions: Nutrient Inputs, Invasive Species, and Multiple Drivers Shape Marine Patagonian Communities

Macarena S. Valiñas, Ricarda Blum, David E. Galván, Martín Varisco, and Paulina Martinetto

Introduction

Interactions between organisms have been historically recognized as one of the main drivers of the distribution and abundance of species (Paine 1966; Rohde 1984). Organisms interact with others either negatively (one participant is benefited at the expense of a negative impact on the other, e.g., predation and competition) or positively (one species benefits from the presence of another species without harm to the

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latter, e.g., mutualism and facilitation; Halpern et al. 2008; Silliman and He 2018). For a long time, negative interactions were considered the most relevant in determining the structure of biological communities, while positive interactions were underemphasized as their impact on communities was thought to be negligible or even null (Paine 1966; Menge and Sutherland 1987). In recent years, the ecological role of positive interactions has been re-evaluated and considered to be as important as negative ones in structuring communities (Silliman et al. 2011). Indeed, under increasingly stressful environmental conditions, competitive interactions can shift to facilitative ones (Bertness and Callaway 1994; He et al. 2013). This becomes particularly important under the current global change (GC) scenario, as the persistence of populations could depend on the amelioration of harsh conditions provided by other species (Bulleri et al. 2018).

Species are climate-dependent, and they have developed adaptations as a response to natural variations in the Earth's climate system, which include events of change from short (e.g., seasonal cycles) to mid and long timescales (e.g., ENSO episodes, glacial to interglacial transitions; Alheit and Bakun 2010; Overland et al. 2010). Since the 1900s the planet is undergoing one of the largest changes in climate ever experienced (see Helbling et al., this volume), with two particularities: (1) the changes are occurring at extremely accelerated rates, and (2) we, human beings, are in part responsible for it (IPCC 2019). Scientists warned that the likely rate of change over the next century will be at least ten times quicker than any climate shift in the past 65 million years (Ripple et al. 2020). The increase in anthropogenic carbon dioxide (CO_2), methane (CH_4), and halocarbon emissions into the atmosphere is the main driver of these changes, being one of their primary direct consequences of warming and acidification of the aquatic systems (IPCC 2019). Since the late 1900s the Earth's average surface temperature has risen ca. 2 °C, and much of this heat has been absorbed by the ocean. Simultaneously, the pH of ocean surface layers has decreased by approximately 0.02 pH units per decade since preindustrial

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times (Bindoff et al. 2019). As a consequence of warming, the planet has been exposed to other changes, including sea level rise, increased ocean stratification, ocean deoxygenation, decreased sea-ice extent, and altered patterns of precipitation and winds, among others (IPCC 2019). Additionally, marine ecosystems have also been impacted by local and regional pressures, such as increased anthropogenic nutrient input to coastal waters, coastal land use change, extreme climatological events, invasive species, and overexploitation of fish and shellfish species (Halpern et al. 2008; Bennett et al. 2021; Vizzo et al. 2021).

Many studies have provided evidence about the impact of different GC drivers on the physiology, behavior, and ecological traits of single species, which often lead to changes in population structure, distributional range, and seasonal abundance (Rabalais et al. 2009; Häder et al. 2014). These studies are invaluable to understand the mechanisms behind the response of different species to GC, in order to make predictions on the functioning of ecosystems under current and future scenarios. More recently, the impact of GC on species interactions started to be considered (Walther 2010; Cahill et al. 2013; Bates et al. 2017). Evidence showed that GC influences virtually every single species interaction in both bottom-up and top-down directions (Doney et al. 2012). Even if species composition is not altered by GC, it has been observed that the strength or direction of interspecific interactions might change (Harley et al. 2006). Since biological interactions intervene and, in many cases, modulate ecosystem functions (e.g., nutrient cycling, primary and secondary productivity) and services to humankind (e.g., food, nutrient cycling, carbon sequestration and storage; MEA 2005), studies incorporating more complex scenarios, albeit challenging, are extremely necessary.

Coastal areas provide many goods and services such as habitat for many species (Barbier et al. 2011), wave energy dissipation (Gedan et al. 2011) and protection against erosion and storm damage (Shepard et al. 2011; Möller et al. 2014), cycling of land-derived nutrients (McGlathery et al. 2007), and sequestration and storage of atmospheric CO_2 (Duarte et al. 2013; Duarte 2017). In particular, coastal intertidal areas are exposed to strong gradients in physical and chemical factors, such as desiccation, nutrient availability, and tidal exposure (Bertness and Callaway 1994; Helmuth et al. 2006). In these stressful environments many organisms live close to their fundamental niche edges (*sensu* Hutchins 1947; Wethey and Woodin 2008), and thus, any change in environmental conditions (e.g., climate) may directly affect their performance by increasing their levels of physiological stress. Such effects can also be indirect, throughout, for instance, changes in predation rates, competition, and facilitation (Gilman 2017; Lord et al. 2017; Yakovis and Artemieva 2017).

Studies aiming to evaluate the impact of GC on species interactions in Patagonian coastal areas are scarce. The reader will have noticed from previous chapters that even in many cases, little is known about GC effects on single species/groups. Throughout this chapter, we aim to show examples of how different GC drivers affect biological interactions of species inhabiting different coastal ecosystems (i.e., salt marshes, macroalgal beds, open coastal waters) of Atlantic Patagonia. In some of these ecosystems, the impact of GC drivers on organisms from different trophic levels has been well explored, thus providing a good basis to make more robust predictions about potential effects on biological interactions.

Increased Nutrient Inputs in Vegetated Coastal Areas of Patagonia

Anthropogenic activities influence the relative strength of bottom-up (i.e., nutrients) and top-down (i.e., grazers, predators) forces on coastal communities by altering both land-derived nutrient inputs and consumer populations (see Eriksson et al. 2009). As a direct consequence of the growing human population and increased settlement and use of coastal areas (Nixon 1995; Valiela 2006), nutrient inputs to coastal waters have increased worldwide leading to eutrophication (e.g., Valiela et al. 1997), one of the main drivers of change in coastal ecosystems around the globe (Malone and Newton 2020).

Salt marshes are one of the most representative vegetated environments along Patagonian coasts. The loss of salt marshes is almost entirely related to degradation as a result of anthropogenic activities (Pratolongo et al. 2013), in particular land fill, fire practice associated with cattle raising, and eutrophication. There are several studies showing that increased nutrients enhance plant growth and biomass production in Argentinean salt marshes (e.g., Alberti et al. 2010, 2011), and most of them also show that the burrowing crab *Neohelice granulata* could partially counteract these bottom-up effects by exerting a strong top-down pressure through herbivory. In this regard, manipulative experiments showed that nutrient enrichment increases biomass of *Sporobolus* spp. by nearly 50% (Daleo et al. 2008). However, top-down pressure exerted by *N. granulata* decreases plant biomass by around 20% and 40% in *Sporobolus densiflorus* and *Sporobolus alterniflorus*, respectively (Alberti et al. 2007). Although some of these studies were conducted in salt marshes outside Patagonia, their authors proposed that similar processes might be operating in Patagonian salt marshes north of 42° 25′S where this crab species occurs in high densities (Alberti et al. 2007).

Increased nutrient availability (mainly N) may lead to more palatable plants which, in turn, may lead to a higher herbivory pressure (Cebrian et al. 2009). In Patagonian salt marshes, the evidence suggests that the relative importance of nutrients and herbivory might vary given that growth as well as herbivory vary throughout the year. For example, Alberti et al. (2011) showed that increased nutrients also increase the consumption of *S. densiflorus* leaves by *N. granulata* in summer and even to a greater extent in fall. Moreover, the impact of nutrients is not uniform through the salt marsh. The maximum effect of increased nutrients on primary production occurs at mid marsh elevations, while no effects of nutrient additions were observed at low or high marsh elevations, where other factors such as anoxia and high salinities seem to be more limiting for salt marsh plants (Alberti et al. 2010).

Nitrogen enrichment strongly enhances the infection by the fungus *Claviceps purpurea* on *S. densiflorus* (Daleo et al. 2013), which reduces seed production and releases alkaloids that decrease herbivory, as shown in other regions (Fisher et al. 2005; Lev-Yadun and Halpern 2007). Thus, fungus effects on plant community structure, as well as on consumers, could have considerable impacts in Patagonian salt marshes. Additionally, increased salinity decreased plant responses to nutrient addition, probably as a consequence of sodium ion interference with ammonium uptake (Daleo et al. 2015). This antagonistic effect is of special importance, as increases in soil salinity are expected to occur as a result of warming (Lynch and St. Clair 2004) and especially in salt marshes (Silliman et al. 2005).

The relative impact of increased nutrients and crabs on plant growth is partly regulated by the physical features of the salt marshes where interactions take place (Daleo and Iribarne 2009). Increases in sediment aeration and nutrient availability due to crab burrowing activities would be more important in poorly oxygenated soils. On the other hand, crab herbivory impact would be more important in areas with coarse sediments and therefore good substratum oxygenation (Daleo and Iribarne 2009). The latest would be the case of northern Patagonian salt marshes inhabited by *N. granulata*.

Another well-represented vegetated system along Patagonian coasts are macroalgal beds (for a detailed description of these environments, see Horta et al., this volume). As a general pattern, one of the first symptoms of increased nutrient inputs to coastal waters is the change in the composition of the macroalgal assemblage, where opportunistic species take advantage over others. When eutrophication is incipient, the increase in macroalgal biomass can have a positive effect by sequestering excess nutrients (Boyer et al. 2002) and by providing abundant food of high nutritional quality for consumers (Hemmi and Jormalainen 2002). However, as the eutrophication process continues, the excessive growth of opportunistic macroalgae can have several detrimental effects. For instance, the massive canopy may grow over the previously dominant species (perennial algae) impeding their photosynthesis (Smith and Schindler 2009). Advanced states of eutrophication are usually characterized by hypoxic or anoxic events, with the consequent decline of associated organisms including macroalgal grazers (D'Avanzo and Kremer 1994; Fox et al. 2009) and the simplification of the original community structure (Valiela et al. 1997; Fig. 1A, B). Under this scenario of high nutrient supply and reduction of consumer abundance, the systems become bottom-up controlled while top-down control may be negligible (Raffaelli et al. 1998). However, in systems where the hydrodynamic forces are strong, the large tidal flush can partially relieve the effect of eutrophication by diluting and exporting land-derived nutrient loads, as well as biological products, minimizing hypoxia-related stress on the biota (Martinetto et al. 2010, 2011). This is the case of San Antonio bay (SAb; 40° 43′ 37″ S, 64° 56′ 57″ W) where the anthropogenic nutrient concentrations, mainly introduced via groundwater from the septic system of the nearby city of San Antonio Oeste, are among the highest registered worldwide (NO_3^-~ 100 µM, PO_4^{3-}~ 7 µM; Teichberg et al. 2010). At that site, the nutrients remain in the system long enough to be assimilated by macroalgae and support high biomass and diversity of primary producers, but not enough to cause hypoxic or anoxic events (Martinetto et al. 2010, 2011; Fig. 1C).

High biomass of nutrient-rich macroalgae can provide a large amount of food of high nutritional quality to grazers, which would explain the higher abundance of herbivore invertebrates reported in nutrient-impacted areas of SAb (Martinetto et al. 2011; Becherucci et al. 2019). The higher invertebrate abundances would in turn

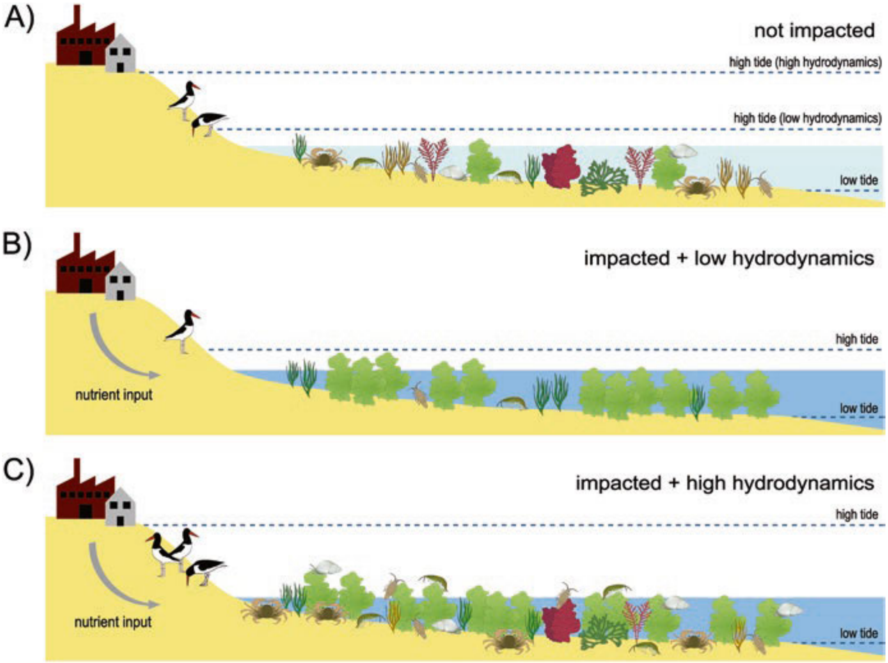

Fig. 1 Responses of the macroalgal community to potential scenarios derived of increases in anthropogenic nutrient input under different hydrodynamic conditions: (**A**) pristine community without nutrient addition; (**B**) anthropogenic nutrient increase under low hydrodynamic conditions, leading to the eutrophication of the system characterized by the overgrowth of opportunistic green macroalgae, anoxic conditions, and a decline of consumer diversity and abundances; and (**C**) anthropogenic nutrient increase under high hydrodynamic conditions as experiencing in Patagonian coasts (e.g., San Antonio bay), where the large tidal flush attenuates the impact of excessive nutrient load, resulting in an increase of both macroalgal and consumer abundances

explain the preference of local and migratory shorebird species for these areas as feeding sites (e.g., oystercatchers and several migratory shorebirds and gulls; Garcia et al. 2010; Martinetto et al. 2010). In fact, some shorebird species changed their foraging strategy from visual-tactile in non-impacted areas to tactile in nutrient-impacted areas, probably prioritizing higher encounter rates with prey of higher nutritional quality that occurs hidden within the macroalgal mats (García et al. 2010).

In nutrient-impacted areas of SAb, herbivores exert a strong pressure on *Ulva lactuca* reducing their biomass by up to 60% (Martinetto et al. 2011). Surprisingly, this macroalga species does not substantially contribute to the intertidal benthic food web (Becherucci et al. 2019). In a manipulative experiment, it was found that increased N supply leads to increased macroalgal biomass only when herbivores were present, which could be related to the additional input of N (mainly NH_4^+) due to excretion (Bracken and Nielsen 2004). Thus, both top-down and bottom-up forces seem to act conjointly in the regulation of macroalgal proliferation in SAb.

Changes in trophic interactions have been reported as a result of higher nutrient inputs in Patagonian intertidal areas. For instance, males of the amphipod *Ampithoe valida* from the Chubut river estuary (i.e., an area exposed to high anthropogenic nutrient inputs) showed higher food consumption rates (FCR) when feeding on macroalgal diets with high nutrient content. By contrast, individuals from intertidal areas less impacted by anthropogenic nutrient inputs showed the opposite behavior: higher FCR when feeding on macroalgae with low nutrient content (Valiñas et al. 2014). Thus, at least in less impacted areas, individuals would be consuming more macroalgae as a way to compensate for the lower quality of the food (Cruz-Rivera and Hay 2000; Duarte et al. 2014). Compensatory feeding mechanisms were also reported in SAb, where it was observed that mesoherbivores increased food consumption rates when the N and C contents of the macroalgae were lower (Martinetto et al. 2011).

Biological Invasions in Vegetated Coastal Areas of Patagonia

In the last decades, the rate of non-native species introduction has increased worldwide, mostly due to increased global trade and transport, leading to widespread changes in the structure and functioning of ecosystems (Seebens et al. 2013; Antón et al. 2019). Many invasive species can benefit some native species (Geraldi et al. 2013; Ramus et al. 2017), although some others can cause extensive negative impacts on native communities (e.g., altering ecosystem functioning, Doherty et al. 2016, or introducing diseases and parasites, Chinchio et al. 2020), and even many of them are responsible for species extinctions (Bellard et al. 2016). In some cases, negative impacts of invaders involve a decrease in the abundances of native species but not on diversity (Antón et al. 2019). This is probably associated with buffering mechanisms conferring ecosystem resistance against exotic species, such as functional redundancy between exotic and native species (García et al. 2014). Anthropogenic disturbance can boost the effects of invasive species on native communities by creating favorable habitats, removing potential predators and competitors, and introducing propagules, thus increasing their chances of establishment in a novel area (Byers 2002; Bertness and Coverdale 2013; Geraldi et al. 2013).

Although there is a large list of species reported as introduced in Patagonian coasts (see chapters by Horta et al., and López Gappa, this volume, Orensanz et al. 2002; Schwindt et al. 2020), only a few are widespread along that range and altered the physiognomy of coastal habitats (Casas et al. 2004; Escapa et al. 2004). This is the case of the barnacle *Balanus glandula*, the reef-forming oyster *Magallana gigas* (formerly *Crassostrea gigas*), the green crab *Carcinus maenas*, and the kelp *Undaria pinnatifida*. The first three have been reported in salt marshes and macroalgal beds of Patagonia, while the invasion of *U. pinnatifida* is mostly restricted to rocky low intertidal and subtidal environments.

The Cases of Balanus glandula *and* Magallana gigas

The barnacle *Balanus glandula* shows a great plasticity as it was found colonizing the branches, roots, and rhizomes of the cordgrass *Sporobolus alterniflorus* (Schwindt et al. 2009; Méndez et al. 2013) in Patagonian salt marshes and also fouling *Magallana gigas* and the endemic crab *Neohelice granulata* (Méndez et al. 2014, 2017). It was proposed that both *M. gigas* and *Sporobolus* spp. would facilitate the establishment of *B. glandula* (Sueiro et al. 2013; Méndez et al. 2015) by increasing habitat structure and complexity and also by enhancing sediment stability (Escapa et al. 2004; Méndez et al. 2015; Fig. 2). In the case of the barnacle-oyster interactions, and based on studies performed with species of similar characteristics in other regions (e.g., Thieltges 2005; Ramsby et al. 2012; Yakovis and Artemieva 2017), barnacle epibiosis could benefit oysters by slowing down desiccation during the low tide and/or by providing camouflage from predators. In addition, since attachment surfaces are a limiting factor in soft-bottom intertidal areas, recruitment on living substrata such as *Sporobolus* spp., *M. gigas*, or *N. granulata* may be beneficial (Foster 1987; Escapa et al. 2004; Méndez et al. 2015). Crabs may also constitute motile vectors speeding the regional invasion of *B. glandula* by contributing the dispersion of their larvae (Méndez et al. 2014; Fig. 2).

The invasion of both *B. glandula* and *M. gigas* in Patagonian salt marshes favors populations of several taxa of invertebrates such as insects, juvenile crabs, isopods,

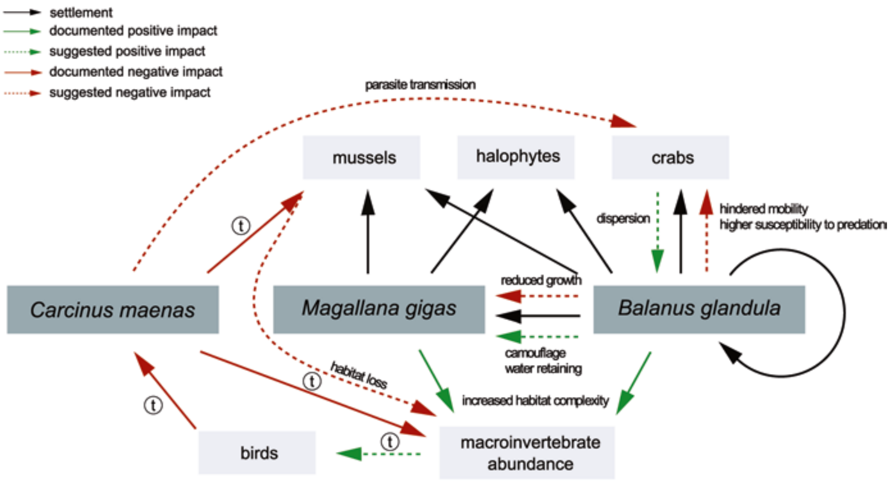

Fig. 2 Schematic representation of documented (solid arrows) and suggested (dashed arrows) interactions mediated by the invasive species *Carcinus maenas*, *Magallana gigas*, and *Balanus glandula* in Patagonian coasts. Trophic interactions are indicated with "t." Both the oyster *M. gigas* and the barnacle *B. glandula* increase habitat complexity benefiting other species by providing refuge. Negative effects of *B. glandula* include limiting mobility and growth of species the barnacles settled-on. The green crab *C. maenas*, which has recently been found to drastically expand in salt marshes of Patagonia, is considered a major threat to these ecosystems by potentially exerting a strong top-down pressure, interfering facilitative mechanisms, and transferring parasites to other organisms

and polychaetes (Escapa et al. 2004; Méndez et al. 2015, 2017), probably by offering protection against predators and alleviating harsh environmental conditions such as heat stress, dehydration, and wave exposure. The physical structure formed by aggregations of *B. glandula* is also important for its own recruitment (Méndez et al. 2017), as barnacle tests serve as substrata for the settlement of conspecific larvae (Qian and Liu 1990; Schubart et al. 1995; Fig. 2). In the case of *M. gigas*, several local and migratory bird species showed higher abundances and feeding rates in oyster-invaded areas, which would be related to the higher abundance of invertebrate prey (Escapa et al. 2004; Fig. 2).

Negative effects have also been reported as a result of *B. glandula* and *M. gigas* invasion. It was proposed that barnacles would increase the risk of dislodgement, reduce growth, or affect feeding activities of oysters as have been shown for other species (da Gama et al. 2008). Moreover, negative effects of the epibiosis of *B. glandula* on *N. granulata* were also suggested (Fig. 2) as barnacles settle on vital zones of the crabs (e.g., walking appendages, ocular peduncles, jaws, and mouth; Méndez et al. 2014) and potentially interfere with their behavior (e.g., walking, feeding, mating). In addition, the elevated contrast of colors derived from the presence of white barnacles growing over brown crabs might also increase their predation risk (Méndez et al. 2014). These potential impacts of *B. glandula* on *N. granulata* deserve further investigation as this crab species exerts a strong top-down control on salt marsh plants and modulates major ecosystem functions (e.g., Costa et al. 2003; Alberti et al. 2007, 2015; Martinetto et al. 2016; Gutiérrez et al. 2018).

The Case of **Carcinus maenas**

In the chapter by López Gappa (this volume), a detailed description of the biology of the green crab *Carcinus maenas*, along with information about its occurrence in Patagonian coasts, was provided. Regarding biological interactions, this species deserves particular attention as it is listed among the ones that cause an overall decrease in all the ecological attributes (e.g., abundance, richness, diversity) of native communities (Antón et al. 2019). Laboratory feeding trials and diet analysis showed that *C. maenas* preferentially feeds on slow-moving and sessile animals, including mussels that act as foundation species (i.e., species that determines the diversity of associated taxa through non-trophic interactions and plays central roles sustaining ecosystem services; Ellison et al. 2005; Ellison 2019) in the intertidal zone (Hidalgo et al. 2007; Cordone et al. 2020; Fig. 2). Based on these results, the authors proposed that *C. maenas* could interfere in facilitation mechanisms mediated by mussels such as the provision of refuge from predation and the amelioration of environmental stress for a large number of invertebrate species (Silliman et al. 2011; Bagur et al. 2016), as it has been observed in other regions invaded by this species. Also *C. maenas* could negatively affect other crab species through the transmission of the nemertean parasite *Carcinonemertes* sp. that was detected for the first time in Argentina in this species (Cordone et al. 2020; Fig. 2). Moreover, this crab has been reported as a novel prey item of the kelp gull *Larus dominicanus*

(Yorio et al. 2020), highlighting a new trophic interaction in Patagonian coasts (Fig. 2). In a recent publication, the authors refer to an "alarming" increase of *C. maenas* population in rocky salt marshes of Nuevo gulf (Battini and Bortolus 2020), although no numerical data were provided to support this statement.

The Case of Undaria pinnatifida

Local studies showed that *Undaria pinnatifida* can outcompete some native macroalgal species (Casas et al. 2004; Raffo et al. 2012; but see Raffo et al. 2009) and proposed light, nutrient, and substratum limitations over native species as potential explanations (Raffo et al. 2015). For instance, manipulative experiments showed that *U. pinnatifida* fronds reduced the photosynthetic active radiation (PAR) levels up to 75% which could potentially affect the growth of native ephemeral macroalgae (Raffo et al. 2015; Fig. 3). Also, in low intertidal and shallow subtidal areas, the holdfast of *U. pinnatifida* covers a substantial fraction of the bottom, which could reduce the surface available for other species. On the other hand, the lack of a strong top-down pressure would partially contribute to its settlement in Patagonian coasts. Although some gastropods and sea urchin species are able to feed on *U. pinnatifida*, the grazing impact of these species is unlikely to control the macroalga (Teso et al. 2009; Fig. 3). Sewage and domestic water effluents in urban areas may also have

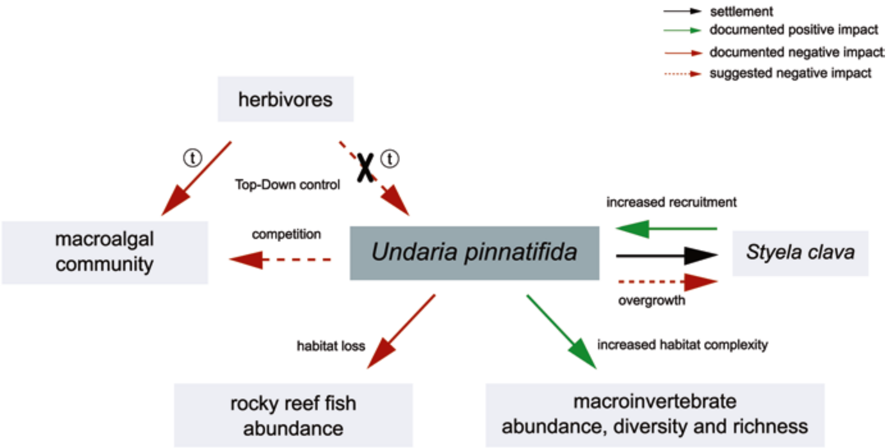

Fig. 3 Schematic representation of documented (solid arrows) and suggested (dashed arrows) interactions mediated by the invasive macroalga *Undaria pinnatifida* in Patagonian coasts. Trophic interactions are indicated with "t." The invasive success of *U. pinnatifida* in Patagonia is probably caused by competitive exclusion, the lack of a strong top-down control, and the facilitation by other organisms such as the ascidian *Styela clava.* Besides some positive effects on macroinvertebrate species, there is growing concern by some authors about the proliferation of *U. pinnatifida* along the Patagonian coast due to its negative impact on local biodiversity

contributed to *U. pinnatifida* settlement as this macroalga can incorporate nitrate, ammonium, and phosphate from the sewage (Torres et al. 2004).

The complex three-dimensional structure generated by the large *U. pinnatifida* fronds (up to 2 m in length) increases species richness, diversity, and abundance of some benthic taxa (e.g., crustaceans, sea urchins, nemerteans, and polychaetes; Irigoyen et al. 2011a) relative to uninvaded areas (Fig. 3). In intertidal areas of SAb, > 80% of *U. pinnatifida* is attached to the invasive ascidian *Styela clava*, and manipulative experiments proved that the recruitment of the macroalga is higher when the ascidians are present (Pereyra et al. 2017). The authors proposed that *S. clava* would facilitate *U. pinnatifida* settlement via moisture retention and protection from grazers, as was reported in other regions (Thompson and Schiel 2012; Yakovis and Artemieva 2017). Moreover, the erect structure of *S. clava* might improve flow dynamics (Harder 2008), increase spore settlement (Bulleri and Benedetti-Cecchi 2008), and facilitate access to light (e.g., Maida et al. 1994) to the kelp. In a recent study (Pereyra et al. 2021), it was found that recruitment of *U. pinnatifida* is higher on live *S. clava* individuals than on mimics of the ascidians, evidencing that a biologic non-trophic effect would be playing a major role in the facilitation process between the kelp and the ascidian than the structure of the ascidians alone. Authors suggested that the siphonal activity of *S. clava* could provide a more oxygenated environment for kelp sporophytes or could help capture more spores. Moreover, the chemical composition of the tunic may favor the emergence of the macroalgae (Paul et al. 2011). However, when macroalga overgrows, it commonly occludes *S. clava* siphons (Pereyra et al. 2017) which could potentially affect water pumping and filter-feeding activities (e.g., Farrell and Fletcher 2006; Fig. 3). Negative effects on fish abundances in low-relief rocky reefs covered by *U. pinnatifida* were also reported in the region (Irigoyen et al. 2011b; Fig. 3).

Impact of Multiple Global Change Drivers on Open Coastal Areas of Patagonia

The Case of Planktonic Communities

In the chapter by Villafañe et al. (this volume), the authors provided a comprehensive description about the impact of different GC drivers (e.g., increased temperature, acidification, increased nutrient inputs, UVR) on planktonic communities. Some of these studies covered more than one trophic level (i.e., phytoplankton-bacterioplankton, bacterioplankton-phytoplankton-microzooplankton) and/or different cell groups (e.g., by cell size, nano- and microplankton; by taxonomic groups, diatoms, small flagellates, etc.), thus providing some clues about potential effects of GC drivers on biological interactions. For instance, it was observed that under high UVR and nutrient inputs, the structure of the community shifted toward a dominance by nanoplanktonic flagellates, which in turn would negatively impact the heterotrophic picoplankton by increasing bacterivory (Cabrerizo et al. 2018). In the same vein, a simulated warming scenario reduced the total biomass of the microbial community, favoring nanoplankton and bacteria (Moreau et al. 2014). In contrast, increased primary production under different future GC scenarios, mainly modulated by increases in the abundance of larger diatoms, was also reported (nutrients, pH, and UVR, Villafañe et al. 2015; nutrients and pH, Masuda et al. 2021). The responses of phytoplankton communities to GC in terms of favored/negatively impacted cell sizes or dominant groups differ depending on the initial composition of the community, their previous light story, and the intrinsic characteristics of the species. However, in terms of growth rates, most studies show a clear trend of increases of this variable regardless of the GC driver or the combination of drivers considered (i.e., UVR, CO_2, nutrients, DOM, or temperature; see Villafañe et al., this volume).

Global change can also lead to a decoupling of phenological relationships, with important ramifications for trophic interactions, including altered food-web structures and eventually ecosystem-level changes (e.g., Edwards and Richardson 2004). For instance, shifts in the Patagonian wind patterns impact phytoplankton communities, not only by favoring smaller cells but also by delaying their blooms for a lapse of about 2 months (Bermejo et al. 2018; Vizzo et al. 2021). Several studies around the globe document drastic declines in the populations of planktonic predators due to climate-related perturbations with the concomitant disruption of predator-prey relationships (e.g., Winder and Schindler 2004). Unfortunately, there is no information about how grazers can impact phytoplankton communities under GC scenarios in Patagonia or how they can be indirectly impacted by the effect of GC on primary producers (but see Spinelli 2013). More studies on this regard are needed given that the outcome of the phytoplankton-zooplankton interactions is expected to be transmitted to all trophic levels, with potentially severe ecological and economic impacts in the region.

The Case of the Squat Lobster Munida gregaria

Long-term data series indicate that some species from Patagonia increased (while others declined) their abundances during the last decades, and examples linking these trends with GC drivers were largely discussed along the different chapters of Galván et al.; Narvarte et al. this volume. While in some cases the impact on the populations is the direct result of the GC stressors acting on the species, in others, the effects are mediated by bottom-up or top-down processes. For instance, top-down impact caused by commercial fishing may reduce the abundance of predators for small fish species, thus decreasing the top-down pressure on these latest (Boersma and Rebstock 2014). In other cases, bottom-up processes triggered by increased nutrient inputs boost primary production in coastal waters, which may indirectly impact primary consumers.

One clear example of increased population abundances in Patagonia is the case of the squat lobster *Munida gregaria* (Varisco and Vinuesa 2015; Diez et al. 2016; de la Barra 2018). This crustacean is found in the southern end of South America and around the coastline of Australia, New Zealand, and the subantarctic Campbell islands. The species has two morphotypes, the *gregaria* type or pelagic-benthic stage and the *subrugosa* type or epibenthic stage. Pelagic juveniles of *M. gregaria* have been documented in the Atlantic ocean in the 1920s (see Varisco and Vinuesa 2010 and references therein). Nevertheless, the *subrugosa* was the only morphotype recorded in the Atlantic coast (not so in the Beagle channel) over the past decades, until the recent appearance of the pelagic morphotype (i.e., *gregaria*) at the beginning of the 2000s. Strandings of this crustacean species along the coast, as well as operational impacts on the shrimp fisheries (de la Garza et al. 2011), are evidence of a recent population growth which was confirmed by direct and indirect observations. A significant increase in the relative abundance and frequency of occurrence of *M. gregaria* was recorded in 2010 and subsequent years in San Jorge gulf (SJg) and adjacent waters (Varisco et al. 2015) and in San Matías gulf (SMg; de la Barra 2018). Moreover, acoustic studies evidence that the population expansion of *M. gregaria* along the Argentine shelf was promoted by the reappearance of pelagic swarms (Madirolas et al. 2013). Even in places where the *gregaria* morphotype was present (e.g., Beagle channel), an increase in pelagic/benthic ratio was observed (Diez et al. 2016).

Munida gregaria plays a key role in the trophic webs of Patagonian and subantarctic coastal ecosystems for two main reasons: (1) it is an important prey item of several marine mammals (Koen Alonso et al. 2000; D’Agostino et al. 2018), fishes (Sánchez and Prenski 1996; Galván et al. 2008; Belleggia et al. 2017), and seabirds (Scioscia et al. 2014), and (2) as the species obtains energy from pelagic and benthic environments, it thus plays a key role in the coupling of both systems (Funes et al. 2018), aside from being a direct link between primary producers and top predators (Vinuesa and Varisco 2007).

Although several hypotheses have been proposed to explain the increase in the abundance of *M. gregaria* and the reappearance of the pelagic swarms in Patagonian coastal waters, the evidence to date is inconclusive. A combination of the following processes has been proposed: (a) a decrease in top-down pressure (Varisco and Vinuesa 2015; Diez et al. 2016), (b) migrations of *gregaria* morphotype from Beagle channel to Patagonian northern waters (Ravalli and Moriondo 2009), (c) a slight increase in the fecundity of the species (Varisco 2013), and (d) an increase of bottom-up forces. Given the broad spatial scale and dynamics of this expansion, migratory process or local increases in fecundity could hardly explain the observed population growth (Varisco 2013). Thus, top-down and/or bottom-up effects linked to GC are more likely behind the *M. gregaria* expansion.

Skates and four commercial bony fishes (e.g., *Genypterus blacodes*, *Genypterus brasiliensis*, *Acanthistius patachonicus*, and *Salilota australis*) were identified as the main predators of *M. gregaria* in the SJg (Sánchez and Prenski 1996). These species are catalogued as species in retraction either because their frequency of occurrence or population biomass has decreased from the 1970s to date (see Galván

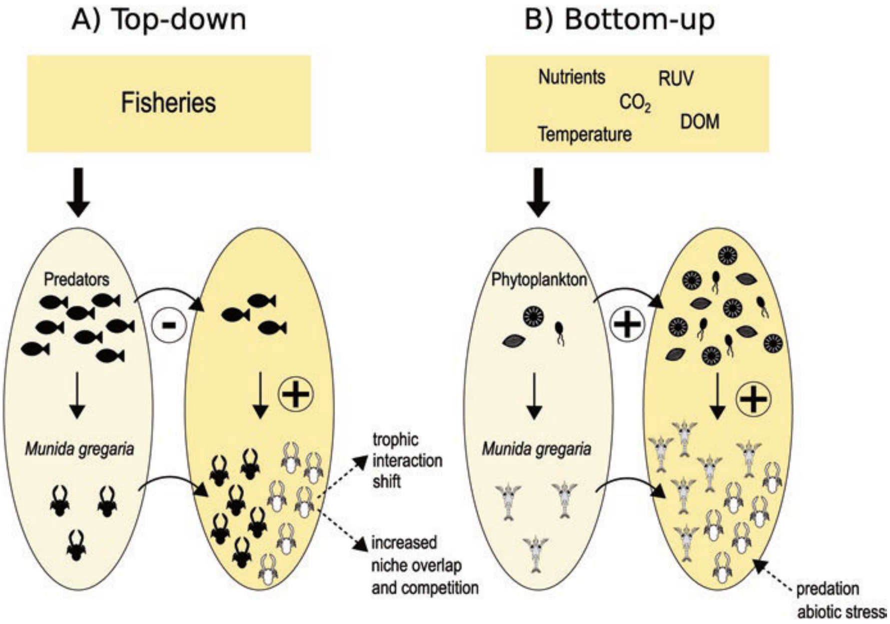

Fig. 4 Main mechanisms proposed to explain the expansion of *Munida gregaria* in Patagonian waters: (**A**) A decrease in top-down pressure on benthic stages of *M. gregaria* (black squat lobsters) leads to a population increase and a subsequent appearance of the pelagic ecotype (white squat lobsters), which potentially explains shifts in trophic interactions as well as increased competition with other organisms of the pelagic realm. (**B**) The increased food availability in the pelagic realm as a consequence of a global-change-induced phytoplankton growth leads to an increase of larval and postlarval stages (gray larvae) as well as the further expansion of the pelagic ecotype

et al., this volume), as a result of commercial fishing or incidental capture (Fig. 4A). Thus, a decrease in top-down pressure on *M. gregaria* has been proposed to explain the expansion of the squat lobster recently observed (Fig. 4A). However, there is evidence contrary to such hypothesis. In the 1980s, the most abundant fish of the assemblage in SJg, the hake *Merluccius hubbsi*, preyed on *M. gregaria* in small quantities (Sánchez and Prenski 1996), but since 2008 the occurrence of squat lobsters in hake's diet increased from < 2% to > 50% (Belleggia et al. 2017), in synchrony with the increase in *M. gregaria* abundance and the decrease in other predator abundances. A similar result was reported at the SMg where *M. gregaria* was not found in the gut contents of hakes collected between 2006 and 2007 (Ocampo et al. 2011) but became the main prey item in samples collected in 2015 (Alonso et al. 2019).

The match between the reappearance of the pelagic swarms and the population expansion of *M. gregaria* could give a clue about some potential advantages that this species would have in the pelagic realm. Different studies reported a positive relationship between large shoals of *M. gregaria* and frontal areas (Diez et al. 2016), as also the presence of shoals in areas of the SJg with increased primary productivity (Varisco and Vinuesa 2010; Ravalli et al. 2013). As mentioned in the previous section, there is a general trend of increased growth rates of phytoplankton communities under different GC scenarios (see Villafañe et al., this volume). Thus, bottom-up processes (i.e., increased food availability) could also explain the increase in the time of residence of *M. gregaria* in the water column, which would further determine the relative abundance of the benthic or pelagic individuals (Varisco 2013; Fig. 4B). However, there are some aspects that we need to take into consideration: (1) as early life stages are the most vulnerable to both predation and abiotic stress (Przeslawski et al. 2015), a larger time that larval stages spend in the plankton before migrating to the bottom could negatively impact the abundance of the squat lobster, and (2) higher prey abundance does not necessarily imply an advantage for consumers. For instance, if food is abundant but of low quality, individuals will not be able to fulfill their metabolic requirements or should invest more time (and energy) to do it (i.e., food compensation mechanisms; Cruz-Rivera and Hay 2000). In such cases, organisms would be allocating less energy to other processes, such as those related to reproduction, which would ultimately affect the reproductive potential of the population.

In addition to the trophic shifts previously mentioned, *gregaria* and *subrugosa* morphotypes have different trophic positions but similar body size (Funes et al. 2018). Pelagic individuals feed mainly on phytoplankton and have a trophic level just over 2 (Varisco and Vinuesa 2010; Funes et al. 2018). Benthic individuals have a trophic level close to 3 and feed on benthic species like crustaceans, foraminiferans, polychaetes, and macroalgae (Romero et al. 2004; Varisco and Vinuesa 2007) and even on fishery discards (Varisco and Vinuesa 2007). An increase in the abundance of pelagic individuals and its consumption by demersal fishes would shorten the food chain length and change the bentho-pelagic dependence of predators. However, also other interactions such as competition for food with pelagic species from similar trophic levels could be triggered, as it was already reported for other squat lobster species. For instance, on the coast of Perú the squat lobster *Pleuroncodes monodon* and the Peruvian anchoveta, *Engraulis ringens* both occur in frontal areas overlapping their trophic niches and spatial distribution (Gutiérrez et al. 2008). In southern Patagonia, it was proposed that pelagic individuals would overlap their trophic niche with the anchovy *Sprattus fueguensis* (Diez et al. 2012), whereas in central and northern Patagonia, a similar situation might be occurring in the pelagic domain with small crustaceans (e.g., euphausiids, pelagic amphipods, and copepods; see table 1 in Botto et al. 2019) and small pelagic fish (Fig. 4B). However, a partial overlap between *M. gregaria* and the Argentine anchovy *Engraulis anchoita* was recently reported in SMg (Luzenti et al. 2021), and authors suggest that the interaction between species could result from an active search and predation of anchovy on squat lobster juveniles.

Perspectives

The reader may have noticed through the chapters of this book that most studies in Patagonian marine systems are based on the direct effects of different GC drivers on individual species or groups (e.g., phytoplankton, intertidal invertebrates), and few studies analyze the effects on biological interactions. In this chapter, we showed that facilitation mechanisms (e.g., settlement, dispersal mechanisms) between sessile invasive species and native fauna are more frequently documented than interference processes. Negative effects of invasive species include top-down pressure and indirect effects on native species by disrupting facilitation by foundation species (e.g., *C. maenas* predation on mussels). Other interference processes were related to decreased habitat suitability (e.g., *U. pinnatifida* and rocky reef fishes) or settlement on vital parts of the individuals preventing its normal performance (i.e., *U. pinnatifida* overgrowing *S. clava*, *B. glandula* growing on crabs).

Also, GC drivers affect trophic interactions through direct and indirect ways. Direct mechanisms include bottom-up processes such as increased macroalgal biomass as a result of land-derived nutrient inputs in coastal areas and increased phytoplankton abundance, a general pattern observed when simulated different future GC scenarios. Yet, these direct effects on primary producers would indirectly benefit primary and in some cases secondary consumers (e.g., invertebrates and birds in macroalgal beds and *M. gregaria* in coastal open waters). In the same vein, top-down pressures mediated by GC processes affect organisms directly by predation (e.g., the invasive crab *C. maenas*, fisheries), but also could have indirect effects through trophic cascades (e.g., *M. gregaria* expansion). Overall, significant changes in the composition and the structure of the communities have been observed in response to all the surveyed GC drivers.

Compared to research done on GC impacts at the species level, studies including multiple species and their interactions are still scarce at a global scale. The Patagonian region in particular is understudied compared to other regions in the world (e.g., Thomsen et al. 2014; Eger and Baum 2020; Reeves et al. 2020). For instance, despite the growing body of literature on the impact of invasive ecosystem engineers in Patagonian coasts reviewed here (see cases of *B. glandula, M. gigas*, and *U. pinnatifida*), the number of studies on this topic still remains very low compared to other world regions (Guy-Haim et al. 2018).

Coastal ecosystems are highly dynamic systems in which all the species are connected through multiple interactions. Therefore, to understand and predict the effects of GC on marine ecosystems of Patagonia and the services they provide, it is essential to know the structure and functioning of their communities. The challenge when predicting the effects of GC lies upon identifying those interactions between species that are most vulnerable to changing climate and other anthropogenic pressures and that, at the same time, are key determinants of the structure and functioning of their community (e.g., foundation species). For these purposes, experimental approaches in combination with observational field data are strongly recommended to develop models aimed to predict future ecosystem changes under different GC scenarios. However, to obtain more robust models and to evaluate the accuracy of their outcomes, it is necessary to count with long-term data series. With few exceptions (e.g., penguins, imperial cormorant, southern right whale; see chapters by Crespo and Quintana et al., this volume), no studies of GC based on long-term data series have been published, and many of the available data series would be not long enough to disentangle the natural variations in climatic variables that operate at mid to long-term timescales (e.g., ENSO episodes) from human-induced climatic effects. Future research therefore should focus on the incorporation of field observations, manipulative experiments, and modeling, which would be the best ecological approach to understand how marine ecosystems as a whole are facing GC in Patagonia.

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Part III

Human Beings and Their Relation with the Environment and Biodiversity in Coastal Patagonia

Temporal Changes in the Utilization of Marine Resources by Hunter-Gatherers of the North-Central Patagonian Atlantic Coast During the Holocene

Julieta Gómez Otero and Ariadna Svoboda

Introduction

The earliest human settlement of Patagonia would have occurred approximately 13,000 BP years ago, during the Late Pleistocene–Early Holocene transition (Borrero 2001; Flegenheimer et al. 2007; Prates et al. 2020). The oldest radiocarbon ages were determined for the inland plateaus, which differ markedly from those of the Atlantic coast (Orquera and Gómez Otero 2007; Zangrando 2018; Prates et al. 2020). The earliest evidences of coastal occupations were reported for the mouth of the Verde stream (7,420 BP; Gómez Otero 2006), the San Matías gulf in the Río Negro province (6,000–4,500 BP; Favier Dubois and Scartascini 2012; Favier Dubois 2013), the northern and southern coast of the Chubut province (5,600–4,800 BP; Gómez Otero 2006; Gómez Otero et al. 2013; Banegas et al. 2021), and the northern and southern coast of the Santa Cruz province (6,000–5,700 BP; Zubimendi et al. 2015; Caracotche et al. 2017). However, this does not mean that the littoral environment was inhabited seven millennia after the first settlement in the inland plateaus. During the Last Glacial Maximum (LGM; ca. 22,000 BP), the sea level was approximately -120 and -140 m below its current position, and the Atlantic coastal plains extended eastward with a variable width between 450 and 100 km (Ponce et al. 2011). After 18,000 BP the global climate turned warmer, and this produced a progressive melting of the glaciers, followed by a global sea level rise. At the Late Pleistocene–Early Holocene transition, when humans arrived to Patagonia, the climate was drier and colder than at the present, most of the Andes

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cordillera was covered by glaciers, the steppe tundra dominated the vegetation, and the sea level was still some meters below the present height (Borrero 2001; Schellmann and Radtke 2010; Ponce et al. 2011). This implies that several areas of continental shelf, now submerged, were then exposed and provided a habitable environment for human settlement. During the Early Holocene the sea level increased rapidly and the coastline reached the current height ca. 7,000 BP (Schellmann and Radtke 2010). At the time of the maximum Mid-Holocene transgression (6,900 to 6,200 BP), the sea level rose 2–3 m a.s.l. This global marine rise produced the flooding of ocean waters over many sections of the Atlantic Patagonian coast and the consequent reduction of the littoral space (Borrero 2001; Schellmann and Radtke 2010; Ponce et al. 2011). The most affected sectors were those of smooth relief and low altitude. After that, a gradual decline toward the current sea level height began (Schellmann and Radtke 2010).

Archaeological and ethnographic data show that before the adoption of horses in the seventeenth–eighteenth centuries and the establishment of villages of European origin at the end of the eighteenth century, Patagonia was only occupied by mobile and small groups of hunter-gatherers whose main prey was the guanaco *Lama guanicoe*. For the study area, zooarchaeological analyses indicate that during the last seven thousand years, the diet of the local populations was composed of guanacos and mollusks in first place and otariids in second place. Marine birds, fish, and small terrestrial mammals were consumed in a low and irregular way (Gómez Otero 2006; Gómez Otero et al. 2009, 2013, 2015, 2017; Svoboda 2015, 2019). Unexpectedly, the "choique" or lesser rhea *Rhea pennata*, the largest and highly nutritional terrestrial bird in the region, is almost absent in the archaeological record: only one bone remain was found at La Armonía M2 site in the San Matías gulf (Gómez Otero et al. 2002). This fact, which has also been determined for other parts of Patagonia, contradicts the written historical reports that after the eighteenth century rheas were intensively exploited (Casamiquela 1983).

Approximately 1000 years ago, ceramics technology was adopted in the north-central coast of Patagonia and the lower valley of the Chubut river – LVRCH (Gómez Otero et al. 2014; Schuster 2014). Isotope studies and gas chromatography analyses of organic residues in pottery vessels show diet diversity (Gómez Otero et al. 2014). The $\delta^{13}C$ values of residues adhered to seven vessels suggest the intake of C_3 plants and/or terrestrial animal proteins and lipids, probably guanaco. In turn, the results of gas chromatography of residues absorbed in eight pottery vessels indicate the presence of plant lipids mixed with variable proportions of terrestrial and marine animal fats (probably fatty fish lipids among them) (Gómez Otero et al. 2014). Bioarchaeological study analyses of oral health and nutrition status in 45 human individuals of the Late Holocene (2,600–200 BP) from the study area and the LVCHR expanded this information (Gómez Otero and Novellino 2011). On the one hand, a slight increase in caries percentage was recognized since 1,000 BP, reaching the highest degree after the European-Natives contact. On the other hand, no nutrition stress or anemia was determined among the whole sample.

Stable isotope studies ($\delta^{13}C$ and $\delta^{15}N$) in collagen, apatite, and tooth enamel of 14 human individuals from the coast and nine from the LVRCH were carried out

(Gómez Otero et al. 2000; Gómez Otero 2007). The individuals buried on the coast exhibited a mixed diet (terrestrial-marine), plant intake, and internal variations in the proportion of marine resources of high trophic level. Some appeared to have consumed > 50% of marine food, others, approximately 30%. By contrast, terrestrial diets prevailed over marine ones on individuals from the valley. However, it is worth noting that isotopic values of an individual from 6,000 BP found 90 km away from the sea indicated a moderate intake (between 10 and 20%) of marine fauna, which reveals the antiquity of the coastal-inland mobility of these populations. The close relationship with the sea and its resources appears to have declined after the adoption of the horse between the seventeenth and the eighteenth centuries (Equestrian period). Indeed, zooarchaeological, bioarchaeological, and isotopic studies show lesser consumption of marine food and a higher intake of terrestrial proteins and carbohydrates. This would have been related to the abandonment of coastal routes because of the ecological requirements of horses (especially freshwater), the reduction of hunting costs of terrestrial preys such as guanacos and rheas, and the addition of European origin foods (cattle, flours, sugar, alcoholic drinks) to the diet (Gómez Otero 2007; Gómez Otero and Moreno 2015). In this chapter we re-evaluate the temporal changes in the exploitation of marine faunal resources by ancient hunter-gatherer populations of the north-central Patagonian coast from the Mid-Holocene to the eighteenth century. Previous and new zooarchaeological and $\delta^{13}C$ and $\delta^{15}N$ stable isotope studies in human skeletal collagen are analyzed and discussed. The data are interpreted in relation to the behavioral aspects of hunter-gatherers as well as to variations in coastal past environment (climate, sea transgressions and regressions) and their consequences on littoral geomorphology and the availability of coastal species.

Past and Present Environment

The study area extends from the mouth of the Verde stream at the border of Río Negro and Chubut provinces (42° S) to Magagna beach, south of Engaño bay (43° 15’ S) (Fig. 1). It includes diverse types of coasts: gulfs, open sea, and the estuary of the Chubut river. The landscape is characterized by a series of interconnected low plateaus < 100 m a.s.l., marine terraces, and cliffs alternating with sandy or pebbly beaches (Súnico 1996; Bouza et al. 2017). Except at 42° S, where outcrops of metamorphic rocks of the Marifil formation appear (Malvicini and Llambias 1974), the geology is simple, with a predominance of sedimentary rocks of Tertiary and Quaternary age (Haller 2000). The intertidal relief is broad and smooth. Access to the sea is possible through large slopes or “bajadas,” low marine terraces, and gullies.

At the time of the earliest evidence of human occupations in the Mid-Holocene (7,400 BP), the climate was warmer than at present and the sea level was about 2 to 3 m a.s.l. (Borrero 2001; Schellman and Radke 2010). About 4500–4000 years ago, when the Late Holocene began, it turned increasingly arid. By 2000 BP the current

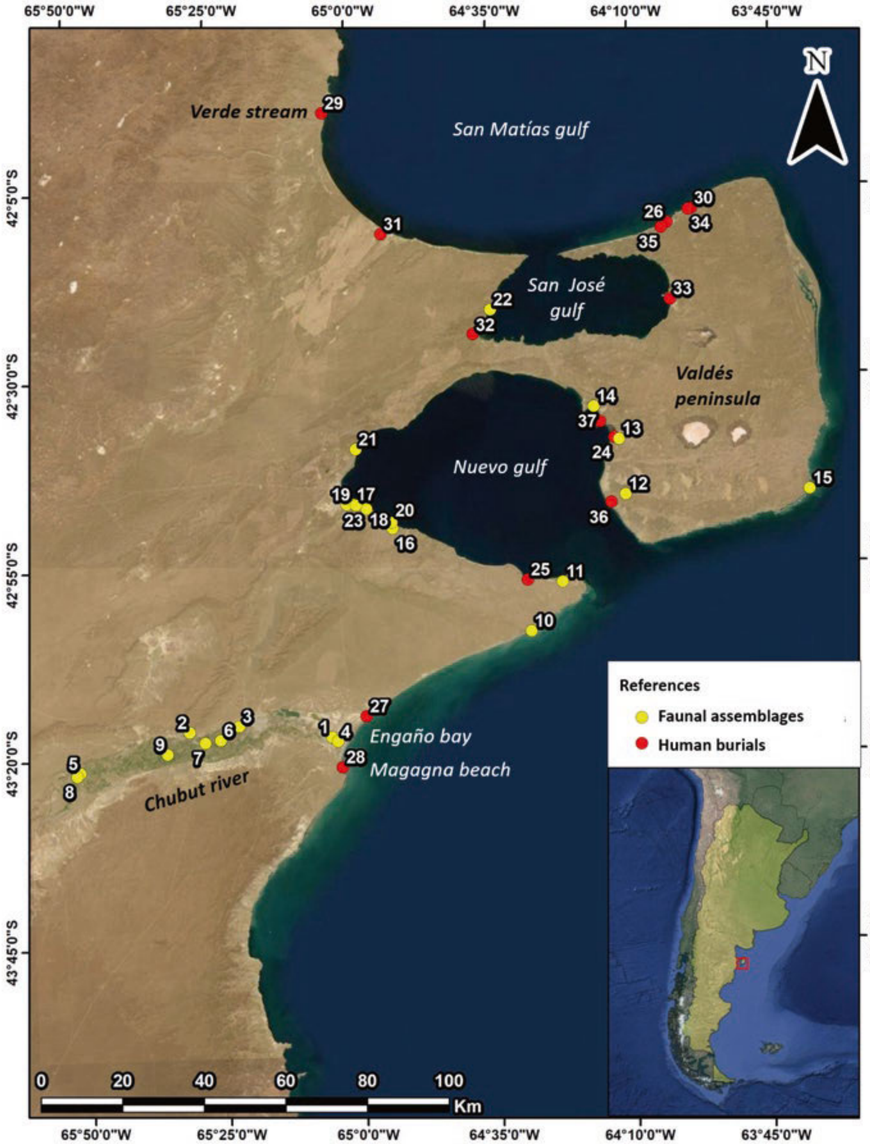

Fig. 1 Study area and distribution of the sites with faunal assemblages (mollusks and vertebrates) and human burials discussed in this chapter. (1) Rawson, (2) Loma Torta, (3) El Inta, (4) El Elsa, (5) Chacra 376, (6) Loma Grande, (7) Chacra 192, (8) Chacra 375, (9) Chacra 247, (10) León point, (11) El Pedral, (12) La Azucena 1, (13) San Pablo 4, (14) Pirámide 1-2, (15) Punta Delgada 2, (16) Cerro Avanzado, (17) Punta Cuevas 2, (18) Médano Grande, (19) Calle Tehuelches, (20) Playa del Pozo, (21) El Doradillo 1, (22) Punta Mejillón, (23) El Golfito, (24) San Pablo 6, (25) Bahía Cracker 4, (26) El Progreso 1, (27) Barranca Norte, (28) Los Cangrejales Sur, (29) Arroyo Verde 1, (30) La Armonía, (31) Rincón de Elizalde 1, (32) El Riacho 1, (33) Flechero del 39, (34) Las Lisas 1, (35) Los Abanicos, (36) Las Ollas 1, and (37) Punta Pardelas 1

climatic conditions and shrub and grass steppe vegetation were already installed (Borrero 2001; Ponce et al. 2011). Between 7,400 and 200 BP, the Patagonian coastline also underwent significant variations because of the ocean global level fluctuations, which promoted the development of accretion geoforms in the regional context (Radtke 1989; Codignotto et al. 1992; Schellmann and Radtke 2010; Isla and Isla this volume). On the west coast of the San Matías gulf, the increasing formation of Aeolian origin accumulations and gravel and shell ridges was recognized from the Late Holocene onward (Gelos et al. 1994). The present-day San José gulf, formerly a tectonic depression, would have been flooded ca. 6,000 BP during the maximum Mid-Holocene transgression (Bouza et al. 2017). In the southern sector of this gulf, Weiler (1998) identified three barrier littoral systems at 6 and 10 m a.s.l. whose radiocarbon ages range between 6,000 and 1,000 BP. In Engaño bay, where the Chubut river flows into the sea, Monti (2000) determined the existence of beach ridge systems as a result of regressive phases of the sea from the Mid-Holocene to the Late Holocene. The development of this sequence of barriers would have occurred between 5,000 and 1,000 BP (see Isla and Isla this volume). The present-day Chubut river course intersects these littoral deposits and separates them into two accretion zones: a highly developed one to the north – Barranca Norte – and a markedly more restricted one to the south (Monti 2000). Finally, in the Magagna beach area, where Isla et al. (2015) recognized that >1.5 m of coastal marine facies are underlying marshes, Gómez Otero et al. (2009) recorded several archaeological layers intersecting marine deposits in Los Cangrejales Sur beach. These layers, dated between 2,100 and 600 BP, indicate that sea level was still higher than at present.

The local present climate is similar to the whole eastern Patagonia: scarce rainfall, strong winds, and cool temperate temperatures (Coronato et al. 2017; see Pessacg et al. this volume). In this regional context, as Valdés peninsula is almost an island, its climate is less arid and milder because of the stronger influence of the Atlantic ocean (Coronato et al. 2017). The freshwater permanent resources are represented by the springs of Grande and Chica salines in Valdés peninsula and the Chubut river. This availability can be supplemented by water reservoirs in dunes and temporary lagoons formed after rains (Álvarez and Hernández 2017). The vegetation is adapted to arid and windy environments. It is mainly dominated by the shrub steppe of the Monte province, but the grass steppe of the Monte-Patagonia ecotone prevails in the south of Valdés peninsula (Bertiller et al. 2017). The tidal regime is semi-diurnal, with average amplitudes of 3.80 m and up to 5.73 m during extraordinary or syzygy tides (Servicio de Hidrografía Naval Argentina, http://www.hidro.gov.ar/oceanografia/tmareas/form_tmareas.asp). At the south of San Matías gulf the amplitude is 6–9 m. This implies accessibility to a variety of marine resources during low tides.

These environmental characteristics affect the integrity and preservation of archaeological assemblages. Wind, precipitations, solar radiation, and current marine dynamics are the most important natural agents in this coastal sector (Gómez Otero 2006). Strong winds generate the migration of sand dunes and the formation of erosion pits. As a consequence, cultural materials are exposed, buried, or mixed with others on the floor of the pits ("palimpsest effect"). Precipitation causes the transport of smaller artifacts which become “trapped” at the bottom of gullies or at the foot of bushes. Solar action mainly affects the bones that were exposed by wind, promoting exfoliation of the bark, bleaching, and, finally, disintegration into splinters. Therefore, the identification of taxonomic and anatomical parts, the determination of age classes, and the recognition of natural or cultural marks become very difficult. In contrast, the bones from stratified contexts show good preservation and integrity. Current marine dynamics can also impact on some archaeological contexts, especially those located at low elevations or erosion fronts exposed to daily tides or waves during storms. Other natural agents include roots, rodents, and the trampling of guanacos, sheep, and horses.

The study area presents diversity and abundance of faunal resources. Invertebrates and fish belong to two biogeographical provinces separated by the 42° S parallel: Argentina province to the north and Magellanic province to the south as far as Tierra del Fuego (Balech and Ehrlich 2008). The gastropods comprise whelks (*Buccinanops*, *Trophon*), and limpets of the Patellidae and Fissurellidae families. The bivalves of greatest commercial value are the scallop *Aequipecten tehuelchus*, the blue mussel *Mytilus edulis*, the Magellanic mussel *Aulacomya atra*, and the white clam *Ameghinomya antiqua*; see López-Gappa this volume). Fish include diverse cartilaginous and bony taxa from rocky substrates and from sandy beach dwelling (see Galván et al. this volume). The most important marine birds in terms of size and abundance are the cormorants *Leucocarbo* spp. and the Magellan penguin *Spheniscus magellanicus*, which are aggregated into large colonies (see Quintana et al. this volume). Among the marine mammals, there are two species of otariids, the South American sea lion *Otaria flavescens* and the South American fur seal *Arctocephalus australis*, which became almost extinct due to overhunting between the eighteenth and mid-twentieth centuries (see Crespo this volume). The southern elephant seal *Mirounga leonina*, various dolphin species, and the southern right whale *Eubalaena australis* are also present. Terrestrial vertebrates correspond to the Patagonian domain (Cabrera and Yepes 1960). The main resources in terms of food are the guanaco and, to a lesser extent, the rhea or “choique,” although the latter has a proportionally higher total lipid content (Saadoun and Cabrera 2008).

Assessing the Temporal Changes in the Diet Through the Invertebrates and Vertebrates’ Remains

To explore temporal changes, we present information on the archaeofaunal assemblages dated by radiocarbon analyses. This comprises radiocarbon conventional ages and their respective calibration by the Marine Reservoir Effect[1]. The

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[1] The Marine Reservoir Effect is a difference in ^{14}C age between contemporaneous organisms from the terrestrial environment and organisms that derive their carbon from the dissolved inorganic carbon (DISC) of the upper oceanic surface layers (100 m thick). Affected radiocarbon dates appear ca. 400 ^{14}C years older than they would if unaffected (Harkness 1983; Olsson 1983).

archaeological information was ordered according to three temporal blocks (TB): TB1 corresponds to Mid-Holocene (7,400–4,000 BP), TB2 to the early Late Holocene (3,990 to 2,000 BP), and TB3 to the final Late Holocene (1,990–200 BP). Twenty-six zooarchaeological and malacological assemblages were analyzed with a chronological distribution ranging from 7,400 BP to 200 BP (Fig. 1, Table 1)

Table 1 Faunal assemblages and chronology data from the north-central Patagonian coast

Area	Archaeological site	Type of site	^{14}C years BP*	Dated sample
San Matías gulf (West)	Arroyo Verde 1 M1[1]	Stratified hearth	7,420 ± 90 (7,020 ± 90)	Shells
	Rincón de Elizalde 1 C1[1]	Stratified shell midden	2,220 ± 70	Charcoal
Valdés peninsula	El Riacho 1 F1[1]	Stratified hearth	2,640 ± 70	Charcoal
	El Riacho 1 F2[1]	Stratified hearth	3,220 ± 70	Charcoal
	Flechero del 39 1 F1 N4[1]	Stratified hearth	2,640 ± 40 (2,240 ± 40)	Shells
	La Armonía M2-SbM 1[2]	Surface refuse context	470 ± 45 (≤200 AP)	Shells
	La Armonía M2-SbM 2[2]	Surface refuse context	460 ± 40	Bone (*L. guanicoe*)
	Las Lisas 1 C1[1]	Stratified shell midden	2,600 ± 60 (2,200 ± 60)	Shells
	El Progreso 1 C1[1]	Stratified shell midden	1,940 ± 60 (1,540 ± 60)	Shells
	Los Abanicos (Fogón 1)[1, 3]	Stratified hearth	380 ± 60	Charcoal
	Las Ollas 1 F1 [1]	Stratified hearth	610 ± 60 (210 ± 60)	Shells
			640 ± 60 (240 ± 60)	Shells
	Punta Pardelas 1 C2[1]	Stratified shell midden	5,580 ± 90 (5,180 ± 90)	Shells
	San Pablo 6 M1[4]	Surface refuse context	400 ± 50	Charcoal
Nuevo gulf (south)	Bahía Cracker 4 M1[5]	Stratified hearth	5,390 ± 130	Bone (*L. guanicoe*)
Engaño bay	Barranca Norte P20 M2[8]	Stratified shell midden	3,810 ± 140	Charcoal
	Barranca Norte 2 N1[1]	Stratified shell midden	3,060 ± 80	Charcoal
	Barranca Norte 2 N2[1]	Stratified shell midden	2,960 ± 60	Charcoal
	Barranca Norte P9-Este L. Sup.[4,6]	Stratified shell midden	2,630 ± 80	Bone (*L. guanicoe*)
	Barranca Norte P4 C1[4,6]	Surface shell midden	2,620 ± 60 (2,220 ± 60)	Shells
	Barranca Norte P5 C1[4,6]	Stratified hearth	2,470 ± 100	Charcoal

(continued)

Table 1 (continued)

Area	Archaeological site	Type of site	^{14}C years BP*	Dated sample
Magagna beach	Los Cangrejales S4 L2a[7]	Stratified hearth	2,040 ± 90	Charcoal
	Los Cangrejales S4 L2c[7]	Stratified hearth	2,290 ± 80	Charcoal
	Los Cangrejales S4 L3[7]	Stratified hearth	1,980 ± 60	Charcoal
	Los Cangrejales S5 L0 Inf.[7]	Stratified hearth	590 ± 70	Charcoal
	Los Cangrejales S5 L1[7]	Stratified hearth	840 ± 60	Charcoal
	Los Cangrejales S6 L Sup.[7]	Stratified hearth	1,490 ± 70	Charcoal

(1) Gómez Otero 2006, (2) Gómez Otero et al. 2002 (3) Gómez Otero and Suárez 2005, (4) Svoboda 2015, (5) Gómez Otero et al. 2013, (6) Svoboda 2019, (7) Gómez Otero et al. 2009, and (8) unpublished radiocarbon age (Code Lab LP-3567). *Radiocarbon age calibrated for the Marine Reservoir Effect

(Gómez Otero 2006; Gómez Otero and Suárez 2005; Gómez Otero et al. 2002, 2009, 2013; Svoboda 2015, 2019). Data collected from Barranca Norte P20 site, yet unpublished, is also included. All contexts come from open air sites, 25 in stratigraphy, one on surface, most of them between 5 and 10 m a.s.l. (Gómez Otero 2006). According to their structure and composition, they comprise (a) stratified or on surface shell middens composed mainly of mollusk shells, (b) stratified hearths with diverse faunal remains, (c) surface archaeofaunal and malacological deposits with discrete spatial limits, and (d) refuse contexts in which archaeological material appears intermingled forming palimpsests (Fig. 2). The archaeofaunal and malacological materials were recovered from subsamples of 0.5 m or 1 m on a side and the height of the deposit, which in most cases did not exceed 10 cm. All materials – archaeofaunal, malacological, and artifacts – were extracted. Most contexts show good preservation and high integrity, except San Pablo 6 and all those of Los Cangrejales Sur. The first is on a coastal lagoon flooded by seawater during syzygy tides (Gómez Otero et al. 2017); the others suffer the action of waves during large swells (Gómez Otero et al. 2009). This causes migration, fracture, burial, and loss of smaller or fragile elements.

For the analyses we selected taxa with anthropogenic modifications (cut and percussion marks and/or burnt damage). As armadillos were generally used as recipients, we only considered the specimens with cut marks. The study excluded specimens assigned to micro-rodents (<1 kg) as in general, their presence is usually associated with natural processes. To establish the relative frequency of each species, we used the Minimal Number of Individuals (MNI), defined as the most commonly occurring skeletal element of taxa in an assemblage (Lyman 2008). The MNI of gastropods was estimated counting the apex or columella. The MNI of bivalves considered the presence of umbo and hinge and the more represented laterality among shells. The MNI of vertebrates was estimated by separating the most

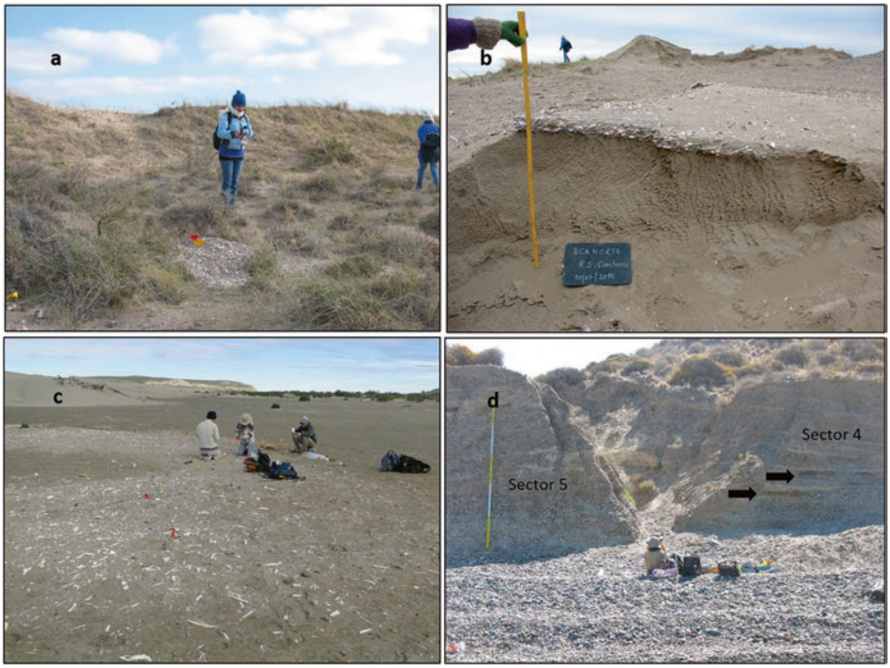

Fig. 2 General view of archaeological contexts: **a**) Little shell midden on surface (BNP4-C1) from the Barranca Norte locality; **b**) stratified shell midden (BNP5 C1) from the Barranca Norte locality; **c**) refuse context of San Pablo 6 (SP6-M1); **d**) stratified hearth layers of Los Cangrejales Sur sectors 4 and 5

abundant element of the taxa into right and left components and using the greater number as the unit of calculation (Mengoni Goñalons 1999). To calculate the fish richness, we applied the Number of Taxa Present (NTAXA) (Grayson 1984).

Mollusk meat was used as food and their shell for technology, i.e., beads or recipients made of *Odontocymbiola* or *Adelomelon* shells (Gómez Otero 2006). In the regional archaeological record, shells appeared associated with diverse materials such as charcoal, ashes, bones, and/or lithic artifacts (Gómez Otero 2006). The malacological analyses show that overall average MNI per sampling is 133 in TB1, 364 in TB2, and 224 in TB3, which indicates a more intensive exploitation in the early Late Holocene (Table 2). As for the selected taxa, in the first two temporal blocks, there is a clear dominance of mussels (blue mussels and Magellanic mussels) (64% and 73.5%, respectively); in the TB3, mussels and limpets reach the same percentage (48%). Nasas are the most represented gastropods in TB1 and limpets in TB2 and TB3. *Trophon* record is only high in Barranca Norte 2 N1, as well as scallops in Rincón de Elizalde 1 C1. *Trophon* is an edible mollusk but it feeds on mytilids (Lasta et al. 1998); therefore it is possible that such specimens entered the sites together with mussels. In summary, along the three temporal

Table 2 Minimal Number of Individuals (MNI) of mollusks and crustaceans' taxa of the studied assemblages

Temporal block	Archaeological sites	*Patella* spp.	*Bucchinanops* spp.	*Trophon geversianus*	Mytilidae	*Aequipecten* spp.	Other mollusks	Total mollusks	Crustaceans
7,400–4,000 BP	Arroyo Verde 1 M1			12	158		5	178	4*
	Bahía Cracker 4 M1		109		28			137	
	Punta Pardelas 1 C2	3	1		71		11	86	20
	Total TB 1	**3**	**110**	**12**	**257**		**16**	**401**	**24**
3,990–2,000 BP	Barranca Norte P20 M2	2	2	1	343		8	356	
	El Riacho 1 F2				21		6	27	6
	Barranca Norte 2 N1	3	31	83	618		1	736	
	Barranca Norte 2 N2		1	11	108		1	121	
	El Riacho 1 F1			2	23		21	46	
	Barranca Norte P9-Este L.Sup.	168		12				180	
	Barranca Norte P5 C1	57			199		1	257	2
	Los Cangrejales S4 L2c	3					2	5	
	Flechero del "39" 1 F1 N4	27	34	15	1039		110	1225	24
	Barranca Norte P4 C1				299			299	
	Rincón de Elizalde 1 C1	114		2	457	403	10	986	9
	Las Lisas 1 C1			2	156		12	170	
	Los Cangrejales S4 L2a	29						29	
	Total TB 2	**403**	**68**	**128**	**3263**	**403**	**172**	**4437**	**41**

1,990–200 BP	Los Cangrejales S4 L3	236					9	245	9
	Los Cangrejales S6 L. Sup.	79					10	89	
	Los Cangrejales S5 L1	77					5	82	
	Los Cangrejales S5 L0 Inf.	143					6	149	
	San Pablo 6 M1		3		3		7	13	
	Los Abanicos 1 F1	99	5	3	890			997	57
	Las Ollas 1 F1				187			187	5
	La Armonía M2 SbM 1	452	28	3				483	
	Total TB 3	**1086**	**36**	**6**	**1080**		**37**	**2245**	**71**
	Total MNI							**7083**	**136**

Gómez Otero (2006), Gómez Otero and Suárez (2005), Gómez Otero et al. (2002, 2009, 2013), Svoboda (2015, 2019)

*_Platyxanthus patagonicus_ crab claws; TB1 (7,400–4,000 ^{14}C BP), TB 2 (3,990–2,000 ^{14}C BP); TB3 (1,990–200 ^{14}C BP). Note: “Other mollusks” include Fissurellidae, Crepidulidae, Veneridae, and Siphonaria specimens blocks, rocky substrate species (limpets and mussels) prevail. This corroborates the results of previous studies and is consistent with the location of the majority of sites in the proximities of rocky intertidal beds (Gómez Otero 2006). Their abundance is striking in the area of Barranca Norte, where rocky intertidal beds are absent in the present, being the beach characterized by thick marine pebble deposits. It is probable that regressive phases of the sea after the Mid-Holocene transgression had buried those previous beds. All these taxa could be extracted in the intertidal during low tides or collected from beach deposits laid by the sea waves after storms.

The proportion of crustaceans is very low. Except for Arroyo Verde 1 M1, where four individuals of crab *Platyxanthu*s were identified, they are represented only by barnacles of the genus *Megabalanus* (Table 2). These barnacle species can be epibionts and predate over other taxa (Roccatagliata et al. 2009). In the Chilean archipelago they were used as food in prehistoric times (Legoupil 2005; Reyes Báez et al. 2011), and this practice continues in the present (Pham et al. 2011). This taxon was also reported and interpreted as food for the southern coast of the San Jorge gulf (Borrero and Caviglia 1978). On the other hand, its exoskeleton might have been utilized as a recipient.

Figure 3 shows the relative frequencies (MNI%) of the terrestrial *versus* marine vertebrate resources through the temporal sequence. Terrestrial resources (guanaco, armadillos, and choique) exhibit a gradual increase during TB2, after 3,500 BP, while marine resources (otariids, birds, and fish) show a decrease from 1,000 BP. Guanaco is present in 77% ($n = 20$) of the samples, while otariids were recorded in 42% (n=11) of the samples (Table 3). Marine birds did not represent an important part of the diet; in agreement with previous data, only cormorants and Magellanic penguins were identified (Table 3). Fish remains are also very scarce in the assemblages. The first evidence of exploitation comes from the Arroyo Verde 1 site (7,400 BP), where 25 sea bass and other rocky species were caught (Table 3). But, as it is the unique site with such high fish abundance, it might be an exceptional case.

With respect to the variability by temporal blocks, the overall average MNI of guanaco per sample is 0.3 in TB1, 1.1 in TB2, and 2.3 in TB3 (Table 3). The oldest clear evidence of its utilization (5,390 BP) was found at Bahía Cracker 4 site. Nevertheless, it is probable that large vertebrate bone fragments found at Arroyo Verde 1 (7,400 BP) correspond to this species (Gómez Otero 2006). Figure 4a shows the increase in its exploitation toward the Late Holocene with a peak between 3,000 BP and 2,500 BP and another lower peak after ca. the seventeenth century during the Natives-European contact period. As an exception, the presence of 12 guanacos was determined in La Armonía M2 site (400 BP) (Table 3). Although guanaco is a lean meat prey, it was used in an integral way by the hunter-gatherer groups of Patagonia, who also took advantage of its fat, hair, bones, and tendons, among other primary products (Casamiquela 1983). The presence of projectile points, “bolas,” knives, and scrapers among most archaeological lithic assemblages indicates their regular hunting and processing (Gómez Otero 2006). Choique is almost absent in the archaeofaunal record (only one tibiotarsus in La Armonía 2 M1), while armadillos are most represented by isolates or few plates; therefore, we did not include them in Fig. 4.

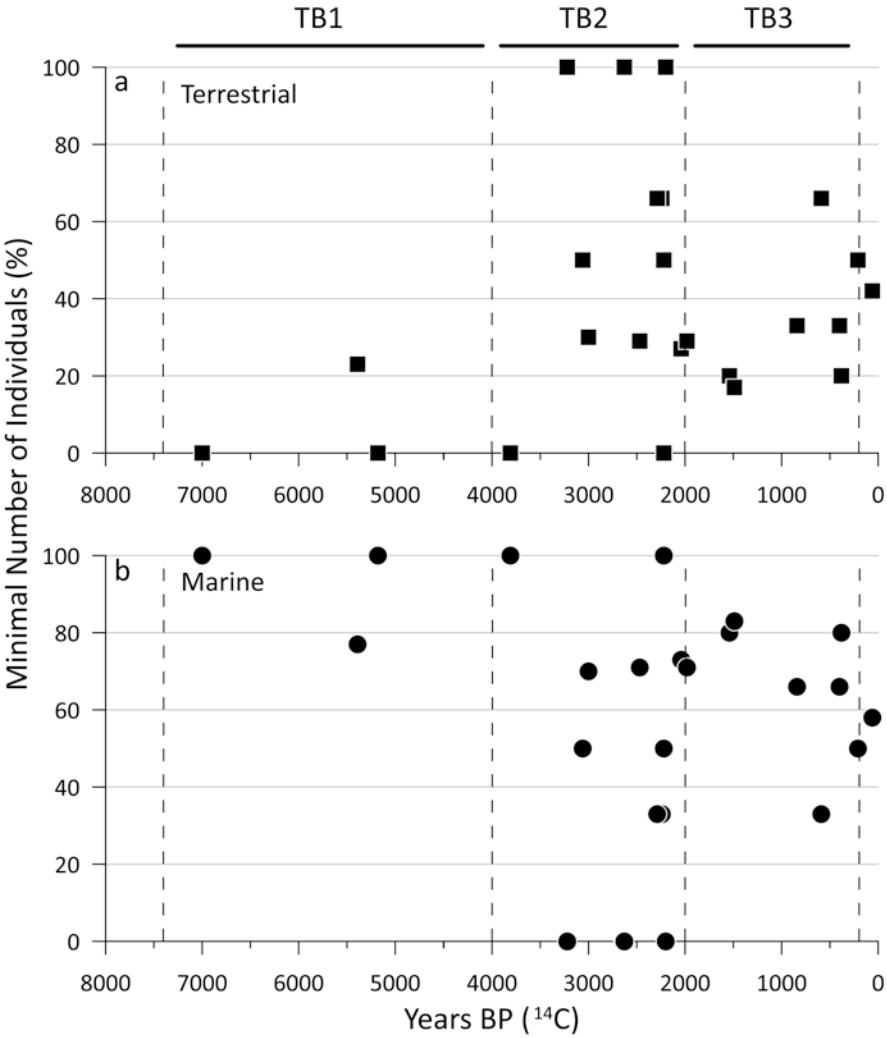

Fig. 3 Relative frequency (as Minimal Number of Individuals, MNI%) of (**a**) terrestrial resources (armadillos and guanaco) and (**b**) marine resources (fish, birds, and otariids) through the temporal sequence in the north-central Patagonian coast (non-calibrated radiocarbon data). Note: Only included bones of armadillos with cut marks

The overall average MNI of otariids per sample is 0.6 in TB1, 0.3 in TB2, and 1.3 in TB3 (Table 3). The first evidence of otariid exploitation (5,390 BP) was also found at the Bahía Cracker 4 site, with a relative abundance of 18%. Figure 4b shows that otariids' relative abundance is variable but moderate (does not exceed 50%) and persists over time. The energetic contribution to the diet is considerable if

Table 3 Minimal Number of Individuals (MNI) of vertebrate taxa of the studied assemblages

Archaeological sites	Fish															Fish total	Marine birds				Otariids				*Lama guanicoe*	Armadillos
	Acanthistius patachonicus	*Pinguipes brasilianus*	*Sebastes oculatus*	*Pomatomus saltatrix*	*Pseudopercis semifasciata*	Nototheniidae	*Polyprion americanus*	*Austrolycus* spp.	*Eleginops maclovinus*	*Netuma barba*	*Odontesthes* sp.	*Triakidae*	Rajidae	Merlucciidae	Indeterminate		*Spheniscus magellanicus*	*Leucocarbo* spp.	Indeterminate	Total marine birds	*O. flavescens*	*A. australis*	Indeterminate	Total otariids		
Arroyo Verde 1 M1	22	1			1											24										
Bahía Cracker 4 M1	2	1	1													4	4			4	1	1		2	1	1
Punta Pardelas 1 C2	1			1											1	3										
Total TB 1	**25**	**2**	**1**	**1**	**1**										**1**	**31**	**4**			**4**	**1**	**1**		**2**	**1**	**1**
Barranca Norte P20 M2																						2		2		
El Riacho 1 F2																									2	
Barranca Norte 2 N1															1	1									1	
Barranca Norte 2 N2	1					1		1	2		3	1				9									2	2
El Riacho 1 F1																									2	1
Barranca Norte P9-Este L.Sup.																									1	
Barranca Norte P5 C1	1								1		1					3		1		1	1			1	1	1
Los Cangrejales S4 L2c									1		1					2			1	1					1	1
Flechero del "39" 1 F1 N4	1				1											2									2	
Barranca Norte P4 C1																		1		1		1		1		
Rincón de Elizalde 1 C1															1	1	1			1						
Las Lisas 1 C1																									2	
Los Cangrejales S4 L2a									4		1				1	6			1	1			1	1	1	1

	Fish																Marine birds				Otariids					
Archaeological sites	*Acanthistius patachonicus*	*Pinguipes brasilianus*	*Sebastes oculatus*	*Pomatomus saltatrix*	*Pseudopercis semifasciata*	Nototheniidae	*Polyprion americanus*	*Austrolycus* spp.	*Eleginops maclovinus*	*Netuma barba*	*Odontesthes* sp.	*Triakidae*	Rajidae	Merlucciidae	Indeterminate	Fish total	*Spheniscus magellanicus*	*Leucocarbo* spp.	Indeterminate	Total marine birds	*O. flavescens*	*A. australis*	Indeterminate	Total otariids	*Lama guanicoe*	Armadillos
Total TB 2	**3**				**1**	**1**		**1**	**8**		**6**	**1**			**3**	**24**	**1**	**2**	**2**	**5**	**1**	**3**	**1**	**5**	**15**	**6**
Los Cangrejales S4 L3						1			1		1					3	1			1			1	1	1	1
El Progreso 1 C1																		2		2			2	2	1	
Los Cangrejales S6 L. Sup.																	1	3	1	5					1	
Los Cangrejales S5 L1									1						1	2			1	1					1	
Los Cangrejales S5 L0 Inf.	1															1									1	1
La Armonía M2 SbM 2	3	1		1			2			5			1	1		14	1			1			1	1	12	3
San Pablo 6 M1																	2	2		4	2	2		4	2	2
Los Abanicos 1 F1	1	1		1	1				1							5		2		2	3	2		5	3	
Las Ollas 1 F1																	1			1					1	
Total TB 3	**5**	**2**		**2**	**1**	**1**	**2**		**3**	**5**	**1**		**1**	**1**	**1**	**25**	**6**	**9**	**2**	**17**	**5**	**4**	**4**	**13**	**23**	**7**
Total MNI																**80**				**26**				**20**	**33**	**14**

Gómez Otero (2006), Gómez Otero and Suárez (2005), Gómez Otero et al. (2002, 2009, 2013), Svoboda (2015, 2019)

References: TB1 (7,400-4,000 ^{14}C BP), TB 2 (3,990-2,000 ^{14}C BP); TB3 (1,990-200 ^{14}C BP) we take into account the average weight and the percentage of subcutaneous fat of *A. australis* and *O. flavescens* (see Crespo this volume). *O. flavescens* and *A. australis* individuals of all age classes and sex were identified in the three temporal blocks, but sub-adults prevailed indicating the exploitation of nearby colonies (Gómez Otero 2006). Analysis of otariids' teeth thin sections indicates that the main capture season occurred from late summer to early autumn (Gómez Otero 2006). Finally, the archaeological record of *A. australis* in the area of Barranca Norte, Bahía Craker 4, and San Pablo 6 shows a different environmental scenario to the current one, as this species is nowadays absent in the area due to the overhunting by sealers between the eighteenth to the mid-twentieth centuries (see Crespo this volume). Stable isotope ratios of carbon and nitrogen studies of Late Holocene and modern samples of *O. flavescens* from the southwestern Atlantic established the much larger impact of modern exploitation on marine resource populations as compared with that by hunter-gatherers (Zenteno et al. 2015). Concerning marine birds, the overall average MNI ratio per sample is 1.3 in TB1, 0.38 in TB2, and 1.7 in TB3, indicating an increase in their exploitation after 2,500 BP (Table 3, Fig. 4c). As well as guanaco and otariids, the first evidence was identified at Bahía Cracker 4 site (5,390 BP). No historical data proves that the Tehuelche natives consumed them; moreover, their presence in the archaeological records of continental Patagonia is very scarce (see Gómez Otero et al. 1998). Their low proportion is striking considering the ease of their capture and the fact that they grouped in fixed colonies during the breeding season (late August to April). It is worth noting that in other sectors of the Atlantic Patagonian coast, the natural incorporation of modern marine bird bones into archaeological deposits has been detected, mainly near penguin colonies (Cruz 2017). As most archaeofaunal assemblages were located over 5–10 m a.s.l., the occurrence of these post-depositional processes is ruled out.

The overall average MNI of fish per sample is 10.3 in TB1, 1.8 in TB2, and 2.7 in TB3 (Table 3). Figure 4d indicates a slight decrease in their relative abundance over the temporal series and an increase in the number of sites with fish remains between 3,000 and 2,000 BP. A fish record decline was determined for the final TB3, which is consistent with several historical documents that emphasize that Tehuelche natives did not eat fish, nor did they know how to obtain them (Gómez Otero 1996). In terms of taxonomic diversity (NTAXA), differences are observed among temporal blocks: the NTAXA of TB1 is 5, that of TB2 is 7, and TB3 is 11, suggesting the exploitation of a greater richness of fish over time. The species in TB1 are exclusively reef fish; in TB2 and TB3 open ocean species were added to the diet. As expected, at the mouth of the Chubut river, the species with the highest relative abundance are estuarine fish such as Patagonian blenny *Eleginops maclovinus* and silverside *Odontesthes* spp. (Table 3), which are very common in environments with continental and sea water mixture. Sea catfish *Netuma barba*, another estuarine species whose current distribution is mainly in the Río de la Plata estuary (García et al. 2010), was recorded in La Armonía M2 (Table 3). Catfish was also determined in Los Cangrejales Sur S4 L2b, a few kilometers south of Engaño bay (Gómez Otero et al. 2009). It can be assumed that fish would have been caught from the shore by the hunter-gatherer groups. The rocky fish may be obtained in the tide pools of abrasion platforms or intertidal shoals. Regarding the technologies of fish harvesting, stone weights that might be

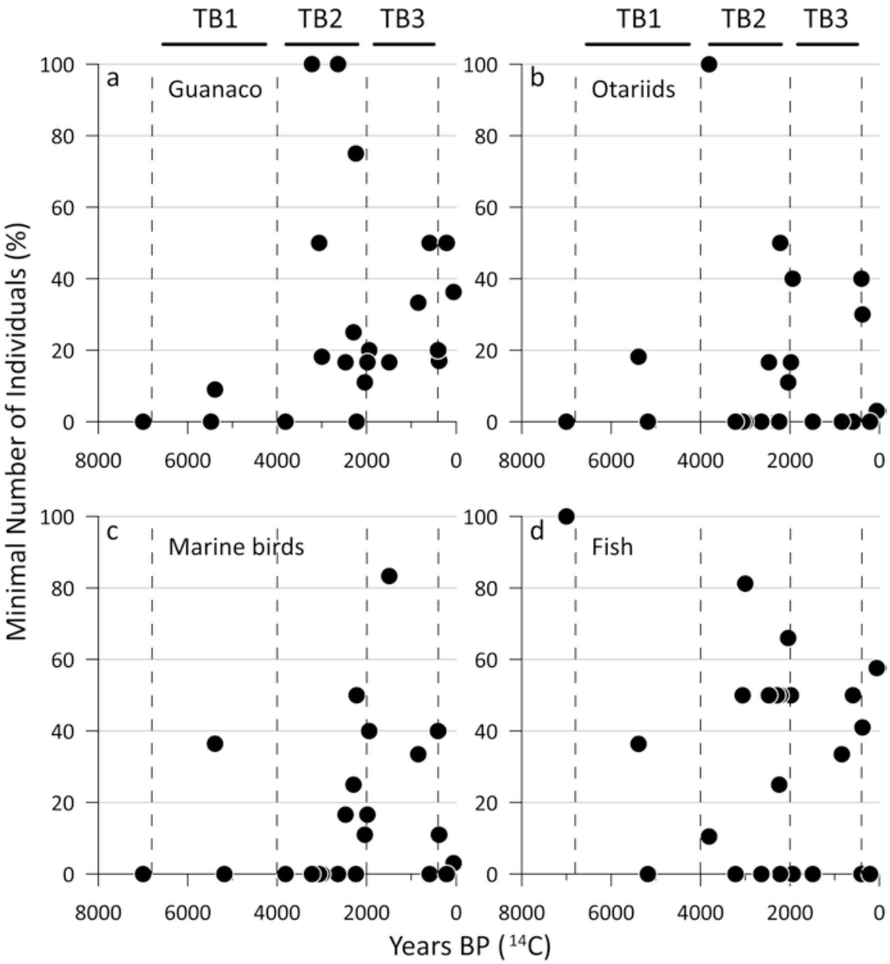

Fig. 4 Distribution of Minimal Number of Individuals (MNI%) values of guanaco **(a)**, otariids **(b)**, marine birds (**c**), and fish **(d)**, through the temporal sequence in the north-central Patagonian coast (non-calibrated radiocarbon data). TB1 (7,400-4,000 ^{14}C BP), TB 2 (3,990-2,000 ^{14}C BP); TB3 (1,990-200 ^{14}C BP)

components of nets or lines were recovered in numerous sites (Gómez Otero et al. 2015). All corresponded to surface contexts and only one to a stratified hearth dated in 590 ± 70 BP (Los Cangrejales Sur; Gómez Otero et al. 2009). The majority are flat marine pebbles with a subcircular or oval shape and two or more notches at opposite sides (Fig. 5a-c). In addition, a fishhook was found in an intertidal pool in the San José gulf coast (Valdés peninsula) and is the only record of this type in Patagonia (Gómez Otero 1996). The artifact is made of wood, 52 mm long, and it is different from common hooks because the tip is longer than the rod shank (Fig. 5d). It was inferred that it was used as a hook to capture rocky fish from the edge of reefs (Gómez Otero 1996). The fishhook would have formed part of a fishing rod made up of a stick, with a line tied to a sinker (Fig. 5e).

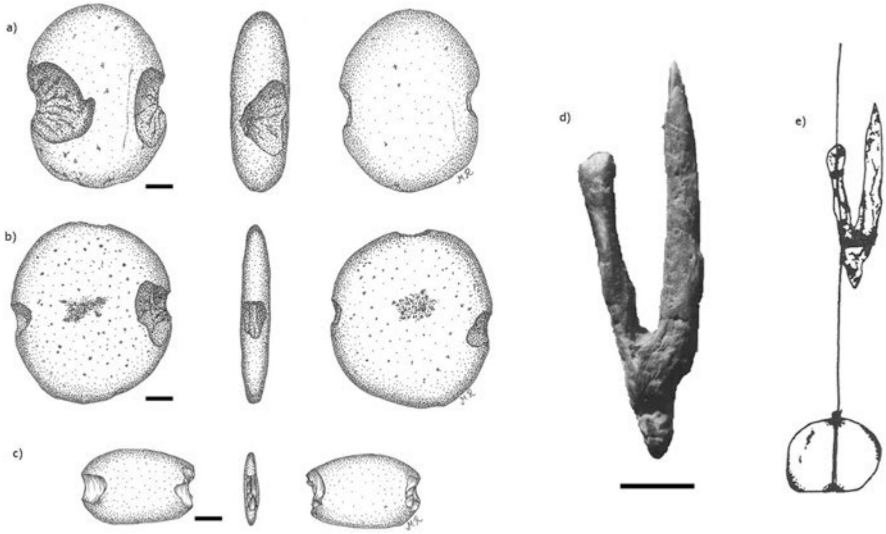

Fig. 5 Fish harvesting artifacts from the study area. Stone weights from: (**a**) Las Ollas, (**b**) Los Abanicos 2, and (**c**) Los Abanicos 3; (**d**) Fishhook of wood recovered in San José gulf (Gómez Otero 1996); (**e**) reconstruction of a fishing line (Gómez Otero 1996). Scale bar denotes 1 cm (Drawing: Mariano Reyes). Figure extracted from Gómez Otero et al. (2015)

The Paleodiet Temporal Variations Through the Analyses of Stables Isotopes in Human Remains

Isotopic values ($\delta^{13}C$ and $\delta^{15}N$) of collagen (organic fraction of bones) of 20 individuals from the northern coast of Chubut and 12 from the LVRCH are presented and discussed (Table 4). The samples had been analyzed in the University of South Florida (Tampa, USA) and data have been published elsewhere (Gómez Otero 2007; Gómez Otero et al. 2001). In this chapter, values from nine individuals are reported for the first time (Table 4); they were analyzed in the Laboratorio de Geología y Geocronología Isotópica (INGEIS) of the University of Buenos Aires/Consejo Nacional de Investigaciones Científicas y Técnicas (Argentina). The samples were calibrated by applying internal and international patterns: L-SVEC, NBS-19, and NBS-22 for ^{13}C and IAEA N1 y IAEA N2 for ^{15}N. $\delta^{13}C$ values were normalized at L-SVEC-NBS-19 scale (Coplen et al. 2006). All individuals were recovered through archaeological excavations, dated by radiocarbon analyses, and also sex and age were estimated (Gómez Otero and Dahinten 1998; Millán et al. 2013). In all of the tested individuals the C/N ratio was 3.2:3.3, which indicates that bone remains were not affected by diagenetic processes. Figure 6a presents the isotope ecology (average values of archaeological faunal samples) and the estimated diet of the individuals (Gómez Otero 2007; Gómez Otero et al. 2000). For this purpose, the isotopic enrichment values established by Bocherens and Drucker (2003) of collagen from the consumer to collagen of the prey are considered. Likewise, the $\delta^{13}C$ and $\delta^{15}N$ values of human diets were assumed to be respectively 1‰ and 4‰ lower than measured bone collagen values. The total sample shows greater variability and higher contribution of marine resources on the coast than in the lower valley values (Table 4, Fig. 6a). It also indicates the prevailing of mixed diets in which terrestrial resources were more important than marine ones. This inter-site variability is clearly shown in Fig. 6a. The cloud points of the coastal sample show a greater dispersion

Table 4 Isotope values (δ^{13}Ccol and δ^{15}Ncol) of human archaeological samples from the north-central coast and the lower valley of Chubut river (LVCHR)

Area	Burial site	Individual	Sex	^{14}C BP	Lab code	13C col. ‰	15N col.‰	Lab code
Valdés peninsula	La Azucena 1[1]	Ind. 1	F	880 ± 50		−14.1	17.2	
						−14.2	15.4	
	La Azucena 1[1]	Ind. 2	F	880 ± 50		−13.2	17.4	
						−13.8	16.8	
	Pirámide 1[1]	Ind. 1	Prob. M	1,200 ± 70		−13.8	15.5	
	Pirámide 3[3]	Ind. 1	M	1,530 ± 50	LP 3286	−13.6	18.3	AIE 37760
	Punta Delgada 1[1]	Ind. 1	M	2,010 ± 50		−11.8	18.2	
	Punta Mejillón[3]	Ind. 1	M	2,410 ± 70	LP 2624	−12.6	18.2	AIE 37758
	San Pablo 4 S 10[3]	Ind. 10	M	2,920 ± 90	LP 3657	−12.8	18.3	AIE 40320
	San Pablo 4 S 1[3]	Ind. 1	Indet.	3,110 ± 90	LP 3262	−14.5	17.1	AIE 37757
Nuevo gulf	Cerro Avanzado 1[3]	Ind. 1	Indet.	2,990 ± 60	LP 2869	−16.6	14.7	AIE 37759
	Punta Cuevas 2[1]	Ind. 1	F	2,640 ± 50		−15.4	13.9	
	Médano Grande 3[3]	Ind. 1	F	2,430 ± 80	LP 3281	−14.4	15.1	AIE 377761
	Calle Tehuelches[1]	Ind. 1	F	2,410 ± 50		−15.8	17.2	
	El Pedral[1]	Ind. 1	M	2,050 ± 70		−16.9	15.2	
	Playa del Pozo[1]	Ind. 1	M	1,540 ± 50		−17.4	13.5	
	El Doradillo 1[1]	Ind 2	M	370 ± 50		−16.8	15.2	
	El Golfito1[1]	Ind. 1	Indet.	770 ± 50		−16.4	14.2	
	El Golfito1[1]	Ind. 2	M	770 ± 50		−16	13.7	
Argentine sea	Punta León[1]	Ind. 1	F	1,050 ± 50		−15.4	18.9	
						−15.4	17.3	
Engaño bay	Barranca Norte1[1]	Ind. 1	F	310 ± 70		−17.9	14.6	
	Barranca Norte1[1]	Ind. 2	Prob. M	310 ± 70		−16.7	15.7	

Table 4 (continued)

Area	Burial site	Individual	Sex	^{14}C BP	Lab code	13C col. ‰	15N col.‰	Lab code
Lower valley of the Chubut river	Chacra 375[1]	Ind. 1	M	6,070 ± 80		−17.6	13.5	
	El Elsa[1]	Ind. 1	F	1,990 ± 50		−17.6	14.1	
	Chacra 376[3]	Ossuary-19	Indet.	1,900 ± 90	LP 2288	−17.6	13.8	AIE 30915
	Chacra 247[1]	Ind. 1	Prob. F	1,690 ± 60	LP-3646	−18.5	11.7	
	Loma Grande[1]	Ind. 1	F	1,480 ± 60		−18.4	14.5	
	Loma Grande[1]	Ind. 2	M	1,390 ± 60		−18	14.5	
	Chacra 192[3]	Ind. 1	M	1,390 ± 80	LP-2149	−20	11.8	AIE 30912
	El Inta Trelew[1]	Ossuary-37	Indet.	720 ± 60		−17.4	14.8	
	Loma Torta[3]	Ind. 1	M	300 ± 50	LP-2181	−17.8	13.9	AIE 30914
	Loma Torta[3]	Ind. 3	Prob. F	270 ± 60		−18.7	13.5	AIE 30913
	Rawson[1]	Ind. 3	M	270 ± 60		−17	15.6	
	Rawson[1]	Ind. 2	M	Modern		−14.2	13.8	

Abbreviations: Prob (probable); Indet. (indeterminate sex); (1) Gómez Otero 2007; (2) Gómez Otero 2012; (3) Unpublished data; AIE: Instituto de Geocronología y Geología Isotópica (INGEIS-UBA-CONICET, Argentina); LP: Laboratorio de Tritio y Radiocarbono (LATYR-CONICET-UNLP, Argentina). Note: All individuals are adults except Loma Torta Ind.3 of 14–16 years old

between the isotopic values of the marine and terrestrial fauna. In contrast, the cloud points of the lower valley sample are narrower and closer to the values of the terrestrial fauna (although there is also an overlap of point assemblages from the two environments). According to the "Linear Mixing Modelling" (Schwarcz 1991), the coastal sample shows a "linear distribution," while the lower valley points out a "linear distribution in a bounded range." The linear distribution is to be expected for diets with varying proportions of consumption of two types of resources: in this case, marine/terrestrial. The linear range-bounded distribution is to be expected when the intake of two resource classes has a smaller range of variation.

Among the 32 studied individuals, ten (31%) presented the highest δ^{13}C and δ^{15}N values indicating an intensive and constant intake of sea resources. All were found on the coast: eight from Valdés peninsula, one from the southern Nuevo gulf (Tehuelches street), and one from the open sea coast (León point). These values allow inferring a mobility annual range closely linked to the littoral environment. The sub-adult Barranca Norte Ind.1 also showed relative high values; however, this could be due to a persistent effect of lactation (Gómez Otero 2007). The individuals with predominant terrestrial diets are 11 (34%). Playa del Pozo is the only one

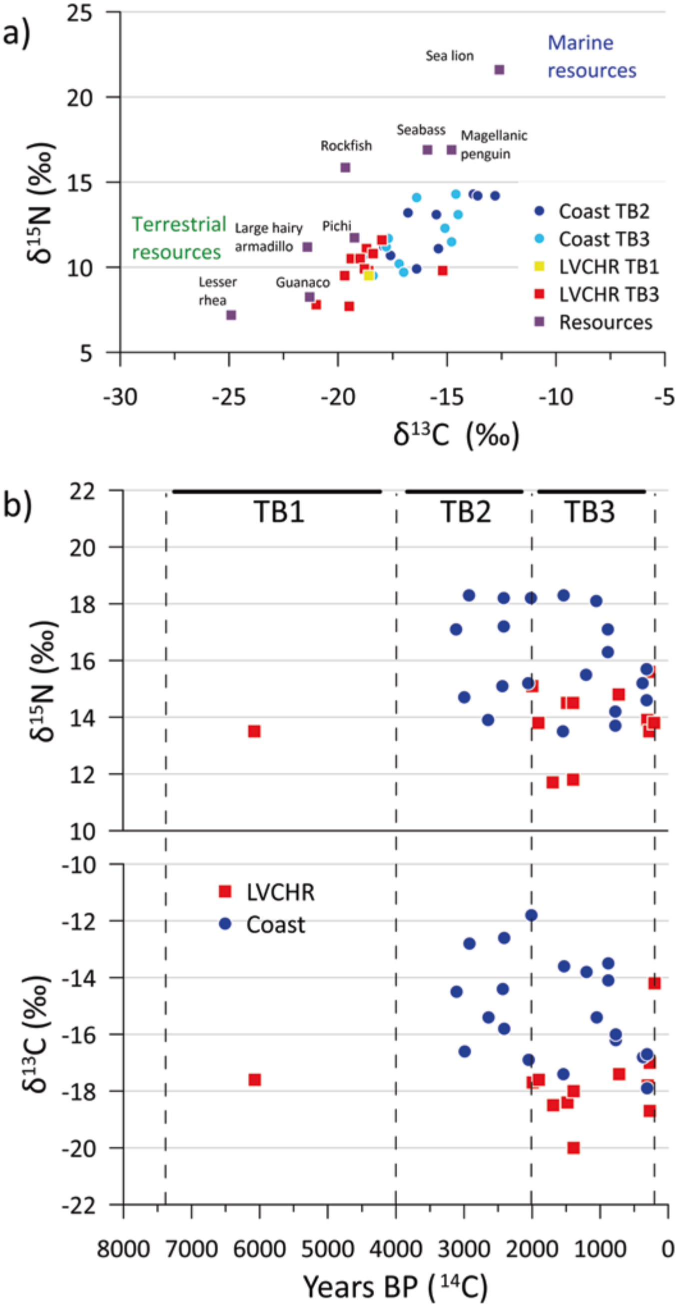

Fig. 6 (**a**) Bi-plot showing the bivariate stable isotope ratios (δ^{13}Ccol/δ^{15}Ncol) of human remains and their prey from the north-central Patagonian coast (Coast) and the lower valley of the Chubut river (LVCHR), after correcting for trophic discrimination factors (TDFs). (**b**) Distribution of collagen δ^{15}N and δ^{13}C values of humans of both areas (coast and LVCHR). Note: TB1 = 7,400–4,000 ^{14}C BP; TB2 = 3,990–2,000 ^{14}C BP; TB3 = 1,990–200 ^{14}C BP (non-calibrated radiocarbon data); isotope values of Loma Grande Ind. 1 and Ind. 2 are identical, so they overlapped

found on the coast, the others come from the lower valley: El Elsa, Loma Grande (n=2), Chacra 192, Loma Torta (n=2), Chacra 247, and Chacra 376. This suggests a greater permanence in inland areas or very low exploitation of marine resources. The remaining 11 individuals (34%) (nine from the coast and two from the lower valley) had mixed diets, with moderate percentages of marine intake (about 30%). Although most of their diet was terrestrial, these individuals – including Chacra 375 found 90 km away from the sea – appeared to have had some contact, perhaps sporadic, with the coast. In sum, the new isotope data confirm the previous paleodietary information that pointed out the higher diversity of the coastal sample. It is worth noting that all individuals of Valdés peninsula show marine diets, which might be related to the insularity condition of the peninsula.

In terms of temporal variability, the whole sample had its limitations as there was only a single individual for TB1 (Chacra 375) and no record of TB2 for the lower valley (Table 4, Fig. 6a, b). Considering the high anthropogenic modifications in the coastal area and the lower valley, this could be due to bad preservation of archaeological records rather than a temporal trend. The $\delta^{13}C$ and $\delta^{15}N$ curves for both environments do not show tendencies until the last 500 BP or European-Natives contact period (Fig. 6b). Most humans from that time showed lower $\delta^{13}C$ and $\delta^{15}N$ values than those of previous periods, which suggests a decrease in marine faunal consumption. This is consistent with the archaeofaunal data.

The temporal trends in the consumption of marine resource by hunter-gatherers from the north-central Patagonian coast show similarities and differences with the archaeofaunal and isotope records from other sectors of the continental Atlantic coast. On the northern coast of Río Negro province, the intensive use of fish was observed around 6,000 BP, evidenced by the on surface record of whitemouth croaker *Micropogonias furnieri* otoliths and lithic weights used in nets (Favier Dubois and Scartascini 2012). Between ca. 3,100 and 2,200 BP, a dominant exploitation of diverse marine resources, mostly of high trophic level (otariids and marine birds), was observed (Favier Dubois et al. 2009). From 1,500 to 420 BP, plants, guanaco, a few proportions of rheas, and small terrestrial vertebrates were added to the marine resources (Favier Dubois et al. 2009). Finally, after the seventeenth century, in the Equestrian period, a shift toward an exclusively terrestrial diet was determined. This would have entailed the abandonment of the coastal area (Favier Dubois et al. 2009). On the northern coast of the San Jorge gulf, zooarchaeological studies in Late Holocene sites (ca. 2,000 BP) indicate a major and intensive use of marine resources, especially mollusks (blue mussels and limpets) and otariids (Svoboda 2019; Svoboda et al. 2019). On the central coast of the San Jorge gulf, archaeofaunal assemblages of the Late Holocene (from 2,900 to 200 BP) show the exploitation of terrestrial and marine prey, although the latter would have played a more important role (Caviglia and Borrero 1978; Arrigoni et al. 2008). The most utilized marine fauna were otariids, followed by mollusks, birds, and fish in small proportions. However, ^{13}C and ^{15}N stable isotope studies of eight individuals from the Late Holocene indicate the predominance of terrestrial resources, as most values are similar to samples from the Patagonian inland plateaus (Gordon et al. 2015). Only one individual, dated to 2,531 ± 45 BP, suggests the intake of marine resources. On the northern coast of Santa Cruz province, the zooarchaeological record exhibits intensive exploitation of marine resources since the Mid-Holocene (Zubimendi et al. 2004; Castro et al. 2008; Moreno 2008). Concerning isotope studies, a great variability was observed: some individuals had sustained a marine diet, others consumed terrestrial and marine resources, and others fed on terrestrial food (Moreno et al. 2011; Zilio et al. 2018). Toward the south, at the mouth of Santa Cruz river, zooarchaeological assemblages show higher exploitation of marine resources than guanaco and other terrestrial fauna (Cruz et al. 2015). In contrast, the human isotope record shows the opposite: predominance of terrestrial resources and less consumption of marine foods (Suby et al. 2009). At the coast of Vírgenes cape, archaeofaunal evidence points out a greater relative importance of marine resources (otariids and, to a lower proportion, birds and fish) (Barberena et al. 2004). This was confirmed by paleodietary information indicating the existence of marine/terrestrial mixed diets (Barberena et al. 2004). In sum, the comparison with the archaeological record of the north-central coast of Patagonia shows higher similarities with the San Matías gulf coast of the Río Negro province and the northern coast of the Santa Cruz province.

Concluding Remarks

Zooarchaeological studies and stable isotope (δ^{13}C and δ^{15}N) analyses in human remains indicate spatial and temporal variability in the subsistence of hunter-gatherer groups on the north-central Patagonian coast between 7,400 and 200 years BP. Throughout these seven millennia, the nutritional spectrum was generally wide and included diverse terrestrial and marine resources. The archaeofaunal record shows that marine resources, especially mollusks and otariids, were important in the diet, but guanaco utilization predominated over time. Among mollusks prevailed the blue and Magellan mussels and limpets. Mussels were more consumed during the Mid-Holocene and early Late Holocene, while both taxa showed equal proportions in the final Late Holocene after 2,000 years BP. The otariids' relative abundance throughout the Holocene suggests that they were exploited in a low proportion, but their representation is higher between 7,400 and 3,500 BP and lower after 1,000 BP. On the other hand, the δ^{13}C and δ^{15}N isotope studies show that until the seventeenth–eighteenth centuries, the prevailing diet included terrestrial and marine proteins in a variable proportion. This allows us to infer different types of mobility and relationships with the coastal environment. Some hunter-gatherer groups would have had a very close and regular relationship, others would have utilized it seasonally or eventually, and others seem to have used it very infrequently. Finally, the archaeofaunal assemblages and the isotope analyses show a decrease in the marine fauna consumption and an increase in the intake of terrestrial resources after the Native-European contact and the Equestrian period. This might be linked to the abandonment of coastal routes because of the ecological requirements of horses (especially freshwater), to the reduction of hunting costs of terrestrial prey such as guanacos and rheas and to the addition of European origin processed foods. In sum, along these seven thousand years, the most relevant changes in the diet occurred after the last five centuries, when European culture and settlers entered Patagonia.

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The Patagonian Fisheries Over Time: Facts and Lessons to Be Learned to Face Global Change

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Introduction

Environmental changes in the ocean result in variations in the abundance and distribution of fish and invertebrate stocks. Increases in temperature and acidification can lead to the loss of marine habitats and changes in the distribution of fish stocks, altering the basic structure of ecosystems. Climate change threatens fish stocks, but also creates new opportunities for fishing: while areas in the tropics are predicted to experience declines of up to 40% in potential seafood catch by 2050, regions in

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higher latitudes are expected to have increases in the abundance of certain fish species, with a consequent greater availability of those stocks (Lubchenco and Gaines 2019).

Along with climate change, the extraction of resources from the sea by people is likewise a component of the global change (GC) affecting the oceans; and, since the middle of the last century – coinciding with the beginning of the so-called Anthropocene (Crutzen and Stoermer 2001) – the exploitation of fisheries has significantly increased the consumption rate of natural resources (FAO 2020). The fishing industry has evolved as a global phenomenon whose market forces can affect fish stocks regardless of their size or site. Strong demand for fish products can induce the overexploitation of fish stocks or cause the retraction of fisheries.

The sustainable management of fishing requires adapting to the various issues stemming from GC. Several examples can be cited supporting the concept that well-managed fisheries are better prepared for environmental changes (Melnychuk et al. 2017, and references therein). These exemplary fisheries have followed scientific advice, effective monitoring, and management in order to ensure sustainability and demonstrated the possibility of balancing economic and environmental priorities to protect oceans and seafood supplies for future generations.

On a global level, the effects of overfishing as the main anthropic stressor of GC were detected early in the fisheries, while the effects of climate change constitute a more recent issue (Bahri et al. 2018; Bertrand et al. 2018). Argentina is no exception, and the concerning fishery problems have been historically more about overfishing than about environmental issues. The first relevant example of fishery overexploitation dates back to 1967, when a foreign fleet collapsed the stock of the "castañeta" (*Nemadactylus bergii*; Bertolloti and Cabut 1986). Subsequently, the stocks of other fish species (i.e., the whitemouth croaker *Micropogonias furnieri*, the Patagonian toothfish *Dissostichus eleginoides*, and Argentine hake *Merluccius hubbsi*), as well as resources targeted by artisanal fisheries (as the blue mussel *Mytilus edulis* or the Tehuelche scallop *Aequipecten tehuelchus*), suffered the consequences of excessive fishing, poor regulations, and a lack of effective controls (Narvarte et al. 2007; Vaz-dos-Santos et al. 2010; Carozza 2012; Sallaberry-Pincheira et al. 2018).

To understand the causes that have repeatedly led to fishing overexploitation, a brief review of the evolution of Argentine fishing is necessary. Even though the first references to fishing in Argentina date from 1821 (Fermepin and Villemur 2004), the activity did not significantly develop until more than a century later (Sánchez et al. 2012; Esaín 2018). By the 1950s, a period of unprecedented flourish took place with the development of the so-called shark fever, driven by the demand for

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vitamin A during the years of World War II. This period determined a substantial internal accumulation of capital that boosted the subsequent development of the national fishing sector (Masid and Mateo 2008) and also constituted the starting point for the development of fishing operations along Patagonian coasts (Mateo 2006). Following the shark's migratory routes, fishing operations expanded from Mar del Plata (38° S) to Rawson (43° 18′ S) and Comodoro Rivadavia (45° 50′ S), resulting in the discovery of new fishing grounds and resources, thus greatly expanding the geographical boundaries of Argentine fishing.

The arrival at Mar del Plata of Belgian immigrants and a trawler fleet in the early 1950s led to the beginning of the deep-sea fishing (Masid and Mateo 2008). By the early 1970s, as a consequence of the depletion of major fishing grounds in the northern hemisphere (Casey and Myers 1998, and references therein), the market demand for finfish grew dramatically on a global level. Several national laws passed during those years strongly promoted fishing and put into effect specific regulations in order to foster foreign investment and establish fishing companies in Patagonia. Fishing fleets expanded intensively, while new technologies enabled increasingly greater harvests, resulting in a major expansion of national industrial fishing and the spread of deep-sea fishing operations into the Patagonian sea.

The development of the Argentine fishing industry, particularly in Patagonia, cannot be understood without considering the historical changes that occurred within the legal framework. Since the foundation of the Republic and until the second half of the twentieth century, fishing resources were legally considered as a *res nullius* – a property not subject to private or state ownership – and state regulations were directed to produce a basic ordering of the activity, assign fishing permits, and establish taxes. As of 1967, with the Presidential Decree N° 17500, the fishing resources became a property of the Argentine State (Esaín 2018), and governmental policies began to have a decisive influence on the development of the sector.

From 1967 to the enactment of the Federal Fishing Act in 1997, the fishing grounds were managed under the so-called olympic system (Esaín 2018), a fishing scheme in which all vessels with fishing permits, mostly unrestricted, compete for a single resource (Bertolotti et al. 2016). This system promoted the "race to fish" that progressively increased catch levels and led to the overexploitation of the main fish stocks. In the late 1960s, a process of successive changes in the legal framework (Esaín 2018) arose to grant new fishing permits, tax exemptions, and specific promotional measures for the acquisition of new fishing vessels and the construction of fish-processing factories in Patagonia, which development largely resulted in the landing records of 1966, 1974, and 1979 (Bertolotti et al. 1987).

The agreements signed in 1987 with the USSR and Bulgaria, and in the 1990s with the European Union, contributed to a dramatic increase in the fishing capacity and catch levels, leading to the overexploitation of several stocks. As a corollary of this expansive process, the number of vessels increased up to seven times from 1960 to 2012 (Bertolotti et al. 2016). In this context, Argentina enacted in 1991 the Law No. 23968 whose Article 5 established the Economic Exclusive Zone (EEZ) in compliance with the United Nations Convention on the Law of the Sea (UNCLOS), which entered into force for Argentina in December 1995. By 1997, the Federal Fishing Act N° 24922 imposed a substantial change in the fishing regime, replacing the olympic system by one based on individual transferable quotas (ITQs). Since 2009, five fisheries were included into the ITQ system (CFP 2020a), while only one of those (the southern hake stock) can be considered relevant in terms of its benefits for Patagonian local economies. The implementation of the ITQ system contributed to an improvement in the biologic sustainability and the economic and labor indicators of those specific fisheries (Bertolotti et al. 2016).

The Patagonian sea contributes to > 75% of the current annual landings (MAGyP 2020). The exporting value of the three main resources caught in the Patagonian fishing grounds during 2019 – the Argentine hake, the Patagonian shrimp *Pleoticus muelleri*, and the shortfin squid *Illex argentinus* – amounted to 1520 million dollars (the shrimp alone constituted 69% of this value), with those total catches representing 82% of the national fishing exports (MAGyP 2020).

In summary, during the second half of the twentieth century, the existing legal framework provided the conditions for a fishing policy strongly influenced by external circumstances, mainly the market opportunities. This policy resulted in a period of sustained development of the fishing sector, leading to a crisis in the availability of fishery resources and putting the affected stocks at risk with respect to their biologic sustainability. Beyond this, it must be added the effects of specific stressors related to climate change, like the increase in water temperature and acidification, the decrease in dissolved oxygen concentrations, and the rise in the sea level, among others. Despite the significance of these overall stressors for the future of fishing productivity and the huge benefits obtained by the relevant societies in Patagonia, such negative drivers conducive to unsustainability have received only scarce attention up to the present.

In this chapter, we focus on the effects of GC on the main Patagonian fisheries considering the relative importance of both the environmental and the anthropic stressors along with their consequences to fishery sustainability. In addition, we will explore the vulnerability of the Patagonian fisheries to GC and examine management options to face its effects. For this purpose, we will focus on the fisheries that provide more benefits for coastal Patagonian people (job creation, regional seafood supply) and, also, produce higher environmental concerns (pollution, fishing wastes). Despite the economic importance of high seas fisheries (i.e., those targeting the Patagonian scallop *Zygochlamys patagonica*, the squid *Illex argentinus*, the austral fishes *Dissostichus eleginoides* and its related assemblage, and the king crab *Lithodes santolla* in San Jorge gulf), they were not considered in this study because they do not fully meet this criterion.

The Patagonian Fisheries

The Ecosystem at the Macroscale

The Patagonian shelf is dominated by the combined effects of strong westerly winds, high-amplitude tides, large low-salinity discharges, and the presence of the neighboring Malvinas current (Matano et al. 2010). The mean circulation is characterized by a broad northeastward flow that intensifies toward the shelf break, where the coastal current merges with the Malvinas current (Fig. 1). South of 49°S, a

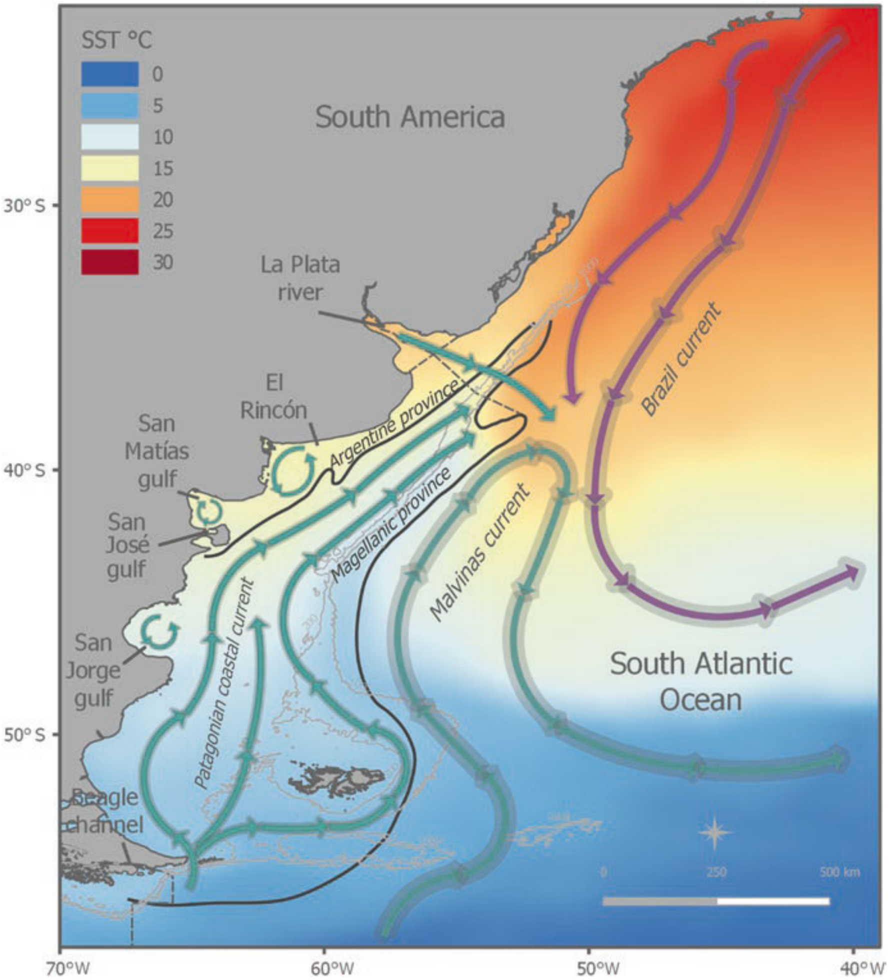


Fig. 1 Schematic representation of the depth-averaged circulation in the southwestern Atlantic region. The mean water temperatures are indicated by the color scale to the left. The various coastal features mentioned in the text, as well as the biogeographic provinces, are shown

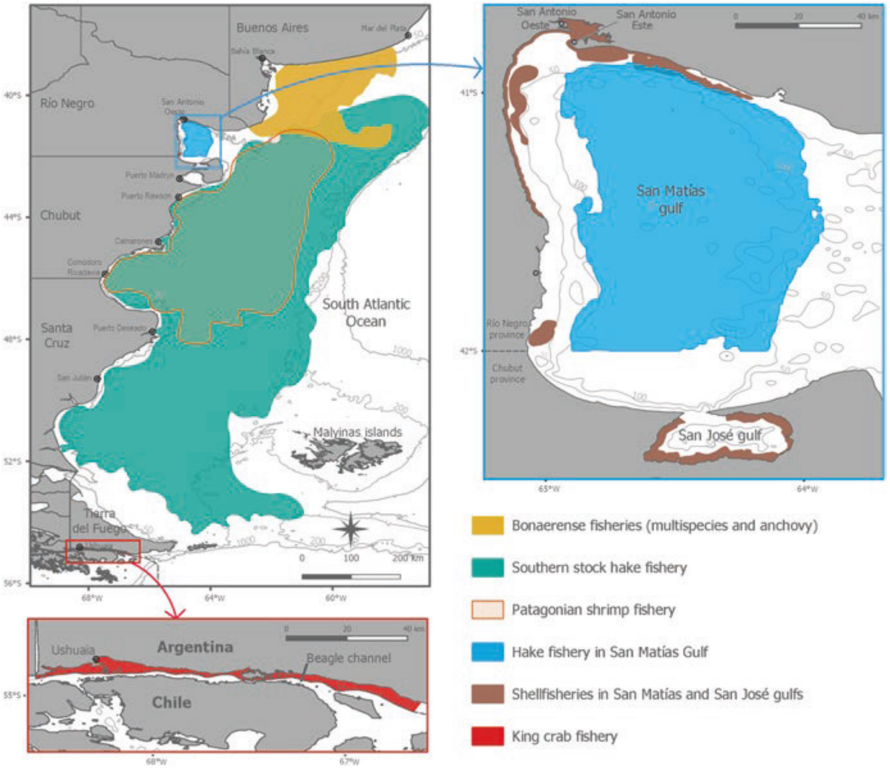


Fig. 2 Geographic range of the Patagonian fisheries covered in the chapter. Main panel: fisheries located over the Patagonian shelf. Right panel: fisheries in the San Matías and San José gulfs and the surrounding fishing landing sites. Bottom panel: the king crab coastal fishery within the Beagle channel

well-defined jet stream occurs within the inner shelf, known as the Patagonian coastal current, generated from the interaction of tidal currents and the Magellan straits' discharge (Piola and Rivas 1997; Matano et al. 2010; Saraceno et al. this volume).

The coastal fisheries targeting invertebrates and fish in the Patagonian ecosystem are mainly distributed within the neritic domain from latitude 38°S down to the Beagle channel (Fig. 2). The northern limit coincides with the northern boundary of the Rionegrino district of the Argentine biogeographic province (Balech and Ehrlich 2008). To the south, the boundary between the Argentine and the Magellanic biogeographic provinces runs in a northeast-southwest direction along the 70 m isobath up to latitude 44°S (Balech and Ehrlich 2008). This limit is highly permeable to several species whose larval or adult stages move in the water masses prevailing on each side of this boundary.

The coastal area of the Patagonian shelf between 38°S and the boundary of the Magellanic province, known as El Rincón, receives the alternating influence of northern warm coastal water and cold temperate waters of the Patagonian current (Piola and Rivas 1997; Matano et al. 2010). Occasionally, this area also receives an intrusion of the cold water of the Malvinas current (Piola et al. 2009). From an ecological point of view, and because of the faunal diversity resulting from the mix of subtropical and subantarctic species, this area, as well as the entire Argentine biogeographic province, could be considered as an ecotone (Balech and Ehrlich 2008). The diverse fish assemblages inhabiting the El Rincón area and the southern Buenos Aires province constitute the support of two main fisheries, the multispecies bottom trawl (hereafter the *Bonaerense demersal fish assemblage fishery*) and the mid-water trawling targeting the northern anchovy stock (hereafter the *Bonaerense anchovy fishery*) (Fig. 2).

On the southwest sector of the Argentine biogeographical province, the north Patagonian gulfs of San Matías and San José (Fig. 1) are affected in general by a macrotidal regime and the influence of subantarctic platform waters. Both gulfs display a strong environmental structure in the warm seasons (spring-summer), with the formation of frontal systems and low water exchange with the adjacent shelf (Gagliardini and Rivas 2004; Saraceno et al. this volume). These gulfs constitute key ecosystems for local fishing fleets, targeting the Argentine hake and other demersal resources (hereafter the *SMG-hake fishery)*, as well as diverse shellfish species, such as Tehuelche scallop *Aequipecten tehuelchus*, mussels, clams, the swimming crab *Ovalipes trimaculatus*, and the small octopus *Octopus tehuelchus*, among others (hereafter the *shellfisheries in north-Patagonian gulfs*) (Fig. 2).

The Magellanic province includes the San Jorge gulf and a wide and extensive platform limited on the southeast by the Malvinas islands and on the west by the continental shores (Balech and Ehrlich 2008, Fig. 1). In this part of the Patagonian shelf the mean annual flux of land-surface heat moves to the sea and the evaporation exceeds the precipitation (Piola and Rivas 1997). The area, strongly influenced by the Patagonian current, presents a vertical structure of water circulation that resembles a two-layer system, with the flow in the upper layer directed toward the northeast and in the bottom layer toward the southwest (Matano et al. 2010). In addition, a large input of deep water coming from Le Maire strait and passing north of the Malvinas islands moves onshore generating coastal upwelling along the southern portion of the Patagonian shelf (Matano et al. 2010). As a result of the influence of subantarctic cold water, this area presents a relatively more homogeneous biota than the north (Balech and Ehrlich 2008). This broad area hosts the two major regional industrial fishing fleets, which target the shrimp (hereafter the *Patagonian shrimp fishery*) and the Argentine hake (hereafter the *southern-stock hake fishery*), along with certain small-scale fishing fleets operating under the provincial jurisdictions of Chubut and Santa Cruz (Fig. 2).

In the extreme south, at a length of 240 km and an average width of just over 4 km, the Beagle channel's water (Fig. 1) presents a low salinity along its basin, a generally nonhomogeneous vertical structure, and a defined seasonality in the temperature (Ballestrini et al. 1998). The circulation in the channel is strongly affected by winds predominantly from the west and the southwest. The water there is diluted by the contribution of continental water originating from the high precipitation rate and melting that characterize this region (Diez et al. 2018). Because of the unique composition of the marine fauna, this area is part of a biogeographic unit that also includes southern Argentina, Tierra del Fuego, and southern Chile. The Beagle channel is the site of the traditional small-scale king crab fishery (Fig. 2).

Synopsis of the Patagonian Fisheries

Summary information on key aspects of Patagonian coastal fisheries (species targeted and bycatch, fleets and gears, landings' trend, research and management) is given in Table 1. The historical facts described previously are also represented on a timeline (Fig. 3A) along with the trend of climatic stressors (Fig. 3B) and detailed landing statistics for each fishery (Fig. 3C–E). In the following section we focus on the main specific issues of the GC affecting fisheries that enable us to identify

Table 1 Essential information on the Patagonian fisheries considered to perform the vulnerability analysis to both natural and human stressors

Fishery	Species (targeted and by catch)	Fleets and gears	Statistics	Research and management	Source
Bonaerense demersal fish assemblage fishery	The demersal fish assemblage comprises over 30 species with the most marketable being the white croaker *Micropogonias furnieri*, the stripped weakfish *Cynoscion guatucupa*, the Patagonian smoothhound *Mustelus schmitti*, and several rays	Trawlers (small and large coastal vessels) use trawl nets. The coastal vessels and artisanal boats use fixed net, purse seine net (lampara), gillnets, hand lines, and fish traps (nasas)	Landings of demersal fishes have been decreasing since 2001 (Fig. 3D)	Research aims to determine the biologically acceptable catch of the main commercial species. Other studies focus on life history, trophic relationships, and changes in the spatial distribution of fishes. Management is shared between the Buenos Aires province and the CFP under olympic system. The TAC is annually stated for the main fish stocks. Other measures include spatial closures to protect critical spawning and nursery areas	Fernández Aráoz et al. (2003); Carozza et al. (2004); Perrotta et al. (2007); Pérez and Ruarte (2013); Elisio et al. (2017); and Rozycki et al. (2020)

(continued)

Table 1 (continued)

Fishery	Species (targeted and by catch)	Fleets and gears	Statistics	Research and management	Source
Bonaerense anchovy fishery	The most commercially significant pelagic resources are the Argentine anchovy *Engraulis anchoita* and the mackerel *Scomber colias*	Trawlers use bottom and midwater trawl nets. Coastal vessels use purse seine nets (*lampara*)	Anchovy landings sharply decreased since 2004. Mackerel landings fluctuated below the TAC since 2012 (Fig. 3D)	Stock assessment is performed through hydroacoustic methods and yield per recruit models. The TAC for both species is annually established by the CFP following the INIDEP advice. Management is shared between the Buenos Aires province and the CFP under olympic system	Orlando et al. (2018a, b); Garciarena and Buratti (2013); and MAGyP (2020)
SMG-hake fishery	The target is the Argentine hake *Merluccius hubbsi*. Other commercial species are the elephant fish *Callorhinchus callorhynchus*, the sharks *Galeorhinus galeus* and *Mustelus schmitti*, the sandperch *Pseudopercis semifasciata*, the silver warehou *Seriolella porosa*, and the flounders *Paralichthys* spp. and *Xistreuris rasile*	Small- to medium-size trawlers use bottom-trawl nets. Artisanal boats operate with midwater longlines	Landings of trawlers grew since 2010, while landings of the artisanal boats decreased (Fig. 3D)	The stock is assessed through research cruises and onboard observer programs. Age-structured population model and multispecies trophic models are applied. The total allowable catch is annually established. The industrial fishing is managed through a system of fixed quotas and the artisanal through a collective quota. Other measures include temporary closures at the spawning and recruitment areas and technical restrictions of the fishing gear	Di Giácomo et al. (1993); González et al. (2007); Ocampo Reinaldo et al. (2011, 2016); Romero et al. (2013); and Svendsen et al. (2020)

(continued)

Table 1 (continued)

Fishery	Species (targeted and by catch)	Fleets and gears	Statistics	Research and management	Source
Shellfisheries in north-Patagonian gulfs	Five mollusks (the purple clam *Amiantis purpurata*, the Tehuelche scallop *Aequipecten tehuelchus*, the mussels *Mytilus platensis* and *Aulacomya atra,* and the Patagonian octopus *Octopus tehuelchus*) are traditionally exploited. Other invertebrates as the geoduck clam *Panopea abbreviata*, the globose snail *Buccinanops deformis*, the razor clam *Ensis macha*, and the crab *Ovalipes trimaculatus*, have become resources since 2003	Artisanal boats operate with benthic dredges and hookah diving. Octopuses are manually caught with iron gaffs in the intertidal and shelters attached to lines in the shallow subtidal	Traditional resources were sequentially depleted in San Matías gulf. Landings of the Tehuelche scallop in San José gulf showed a reduction trend (Fig. 3E)	Research has frequently comprised the assessment of stock biomass previously to harvesting. Management measures include minimum commercial sizes, harvest season, no-take areas, and daily limits in catch and effort, among others. Access is allowed to artisanal fisherman through individual fishing licenses and under olympic system. Co-management schemes were occasionally put in practice	Narvarte et al. (2007, 2011); Morsan et al. (2010); Storero et al. (2013); Soria et al. (2016); and De la Barra et al. (2019)

(continued)

Table 1 (continued)

Fishery	Species (targeted and by catch)	Fleets and gears	Statistics	Research and management	Source
Patagonian shrimp fishery	The target species is the Patagonian shrimp *Pleoticus muelleri*. The common hake is composed most of the bycatch and discards. One hundred other species (bony, cartilaginous, and jawless fishes) is composed of the bycatch	Fleet is composed of small-size, medium-size, and high seas ice-chilling and freezing trawlers. Most of the trawlers use double-rigged otter-trawl nets. Artisanal boats use a single shrimp net	Landings increased from 2006 to 2018, but showed a downward trend in 2018–2019 (Fig. 3C)	Biomass and recruitment are assessed through research surveys. Studies on life cycle, migrations, and the environment are also performed. The management (except in San Matías gulf) is shared by the provinces of Chubut and Santa Cruz plus the CFP. Resources are allocated through catch authorizations under olympic system. Technical measures include limits to the size and power of trawlers, the use of selective devices, and permanent, seasonal, or ad hoc closures, among others	Fernández et al. (2007); Góngora et al. (2009); Bovcon et al. (2013); Boschi (2016); CFP (2018); and Góngora et al. (2021)

(continued)

Table 1 (continued)

Fishery	Species (targeted and by catch)	Fleets and gears	Statistics	Research and management	Source
Southern-stock hake fishery	The target species is the Argentine hake. Bycatch species mostly include the shortfin squid *Illex argentinus*, the elephant fish *C. callorhynchus*, several skates, the kingkip *Genypterus blacodes*, the Patagonian shrimp, and the long tail hake *Macruronus magellanicus*	The fleet is essentially composed of medium-size and high-seas (freezing and ice-chilling) trawlers, all equipped by otter trawls	The stock was overexploited during the 1990s. Landings have remained in the order of the allowable catch since 2008 (Fig. 3C)	The stock assessment is conducted by means of the virtual population analysis method combined with an extended-survivor analysis. Stock abundance and recruitment are assessed through research cruises, and discards are estimated from onboard observer programs. The management is performed under ITQs. Technical measures include permanent closure of areas, legal mesh size, and the use of selective devices	Macchi et al. (2004), Álvarez Colombo et al. (2011), Bovcon et al. (2013), Gil et al. (2019), and Santos and Villarino (2019)

(continued)

Table 1 (continued)

Fishery	Species (targeted and by catch)	Fleets and gears	Statistics	Research and management	Source
King crab fishery	The target species are the Southern king crab *Lithodes santolla* and the false king crab *Paralomis granulosa*	The fleet is composed of small coastal vessels (<15 m length), and the only fishing gear allowed is the truncated-conical baited trap, in variable numbers along a ground line	The fishery was declared as "collapsed" in 1994 and a closed fishing area near Ushuaia was established. No recovery signs have evidenced. The landings of both species were constant during 2010–2020 (Fig. 3E)	Research and surveys have been focused on the basic biologic aspects to periodically assess the effect of fishing on the stocks. They have provided the provincial authorities with useful information for the fishery management rules over time. The resources are allocated to local fishermen, and technical measures include the known 3S rule (selection by sex and size and seasonal closures)	Lovrich and Tapella (2014) and references therein, Boschi (2016), MAGyP (2020)

Abbreviations: *CFP* Consejo Federal Pesquero, *TAC* Total Allowable Catch, *INIDEP* Instituto Nacional de Investigación y Desarrollo Pesquero, *ITQs* Individual Transferable Quotas

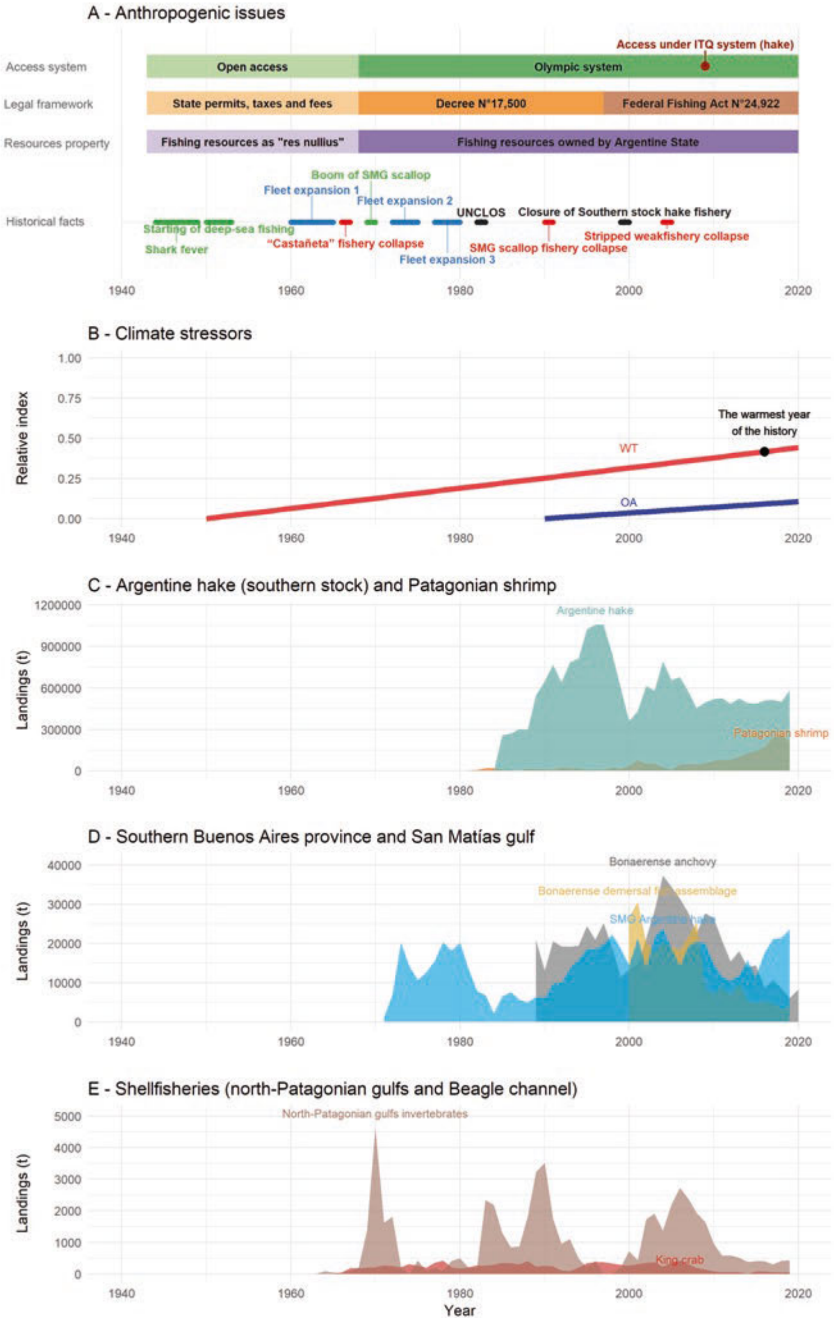


Fig. 3 Timeline of the historical events acting on the Patagonian fisheries from 1940 up to nowadays. Panel **A** represents the occurrences of significant anthropic issues during Patagonian fishing history. Panel **B** shows the change in the specific climate-induced environmental stressors of water temperature (red line, relative index) and ocean acidification, expressed as the IPCC Δ-surface-pH of the seawater (blue line). Panels **C**, **D**, and **E** indicate the total landings, expressed as *t*, of the respective Patagonian fisheries. Abbreviations used: *SMG* San Matías gulf, *IPCC* International Panel on Climate Change, *FFA* Federal Fishing Act, *ITQ* individual transferable quota

whether the environmental drivers (i.e., rising sea temperature, acidification) are more relevant than those belonging to the human dimension (i.e., overexploitation, market forces) of the GC.

Evidence for the Global Change in the Patagonian Fisheries

Until now, the effects of GC on the Patagonian coastal ecosystems, and particularly on their fisheries, have been poorly studied. In part, this is because the attention was put on stressors that produce strong effects on the mid-term, like overfishing and eutrophication. Conversely, climate change stressors, as warming or acidification, are often viewed as having long-term and weak effects, and thus less attention was put on them (Barletta et al. 2010). Nevertheless, climate change occurring in the Southwest Atlantic ocean (Orselli et al. 2018; Franco et al. 2020; Villafañe et al. this volume) has the potential to affect invertebrates, fish, and fisheries through its influence on habitats, possibly modifying recruitment (Acha et al. 2012; Rodrigues et al. 2015), the use of breeding and nursery habitats (Jaureguizar et al. 2016a, b, 2020, 2021), and ultimately the coastal and artisanal fisheries settled across the littoral system (Jaureguizar et al. 2016b; De Wysiecki et al. 2017; Bertrand et al. 2018). The question thus becomes whether evidences of change mostly due to climate (physicochemical) and/or human drivers are available.

Physicochemical Changes and Consequences to Fisheries

According to the recent changes and future projections of ocean conditions at a regional level (Hoegh-Guldberg et al. 2014), the surface layers of the South Atlantic Ocean (0–700 m depth) have warmed 0.378 °C over the last 60 years (Fig. 3B). Trends in the sea surface temperature (SST) indicate, however, considerable subregional variability. Given the essential role that temperature plays in the life histories of marine organisms (Poloczanska et al. 2016, and references therein), the velocity of the thermal change ultimately determines the speed at which populations must either move from, adapt to, or acclimate to changing sea temperatures (Pörtner 2002; Hoegh-Guldberg and Bruno 2010; Burrows et al. 2011). Although several areas of the Patagonian region indicated no changes, both at the north and south of the ecosystem of the Patagonian fisheries, the velocity of the SST isotherm has shifted in a north-south direction between 10 and 20 km per decade over the period 1960–2009 (km per decade, see Burrows et al. 2011). Saraceno et al. (this volume) report an SST increase of 0.2 °C per decade with no trends in the bottom layer of El Rincón during 1980–2016. A positive trend in SST of around 0.3 °C/decade is also reported for San Jorge gulf. For the north-Patagonian gulfs, studies lack precision to identify the changes in the physical variables over the last decades. Finally, for the southern areas of the Patagonian shelf and the Beagle channel, no specific trends in temperature have been reported; however, the predicted change in the water mass characteristics could lead to the increase of the vertical stratification (Saraceno et al. this volume).

Besides the observations and projections for the oceans worldwide, certain specific changes have been reported regionally at the different latitudes of the Patagonian fisheries ecosystem. On a seasonal scale, the prevailing winds and rivers within the southern coastal shelf of the Buenos Aires province (El Rincón) are the main mechanism driving the extension and contraction of the estuarine system and the latter's interaction with the surrounding shelf waters (Subantarctic waters; Palma et al. 2004). Although no evidence of a significant interannual warming trend in the coastal system can be cited (Delgado et al. 2014; Luz Clara et al. In press), the poleward displacement of wind patterns over the South Atlantic Ocean reported during recent decades has led to a southward expansion of the subtropical gyre and a southward extension of the Brazilian current resulting in a warmer outer-shelf water (Franco et al. 2020). The wind pattern variation, with incidence on the water mass north-to-south advection, will affect the seasonal extension of Magellanic resources northward in association with cold and salty waters (e.g., the apron ray *Discopyge tschudii*, Cortés et al. 2011). The same migratory movement could occur for the Patagonian smoothhound (*Mustelus schmitti*), a species for which El Rincón fulfills its life requirements. During the reproductive season (spring), the abundance of this shark exhibits spatial onshore-to-offshore migration related to a change in the hydrologic conditions. A drop in the nearshore salinity, due to a higher freshwater discharge of the Negro and Colorado rivers, may induce individuals located inshore to move offshore toward the neighboring deeper water, a pattern reflected in both the higher abundance (Jaureguizar et al. 2016a, 2020) and the occurrence of reproductive aggregation in deeper coastal water (Elisio et al. 2017). The Negro river discharges *ca*. 90% of the freshwater entering the Southern Oscillation Index range (Pasquini and Depetris 2007). The increased frequency of extreme rainfalls, as predicted during periods of El Niño Southern Oscillation (Tedeschi et al. 2016), can have a profound effect on salinity and on the spatial coverage of that shark's preferred habitat as well as a substantial impact on the fishing mortality occurring in the breeding and juvenile areas of Anegada bay, which change would affect shark recruitment. Changes in fish distribution have been also identified for the demersal-pelagic assemblage in the middle Patagonian coastal region (Galván et al. this volume).

In the anchovy *Engraulis anchoita*, decreasing trends in egg abundance (a proxy of biomass) were correlated with positive SST anomalies and high salinity conditions in the northern Argentine shelf (Auad and Martos 2012). A long-term analysis (1991–2017) also revealed a declining pattern in anchovy landings (between 34°S and 41°S), together with a decrease in the size and the weight at a given age (Prenski et al. 2016, and references therein). The commercial catches were substantially below the total allowable catch estimated by routine scientific hydroacoustic assessments (Orlando et al. 2018a, b). Franco et al. (2020) relate the long-term patterns of anchovy landings to climate-change drivers influencing the oceanographic conditions over the Southwest Atlantic ocean.

Although the surface isotherms for the central Patagonian platform appear to move relatively slowly (Burrows et al. 2011), the effects of this change could be significant for critical biologic processes in certain species. For example, Marrari et al. (2018), analyzing the relationships between the recruitment of the hake's southern stock and the environmental conditions for a 17-year period by satellite-mediated chlorophyll assessments and SST data, found that hake recruitment and larval survival were favored by the combination of a colder-than-average fall SSTs and high spring-chlorophyll concentrations along with a late chlorophyll maximum in the spawning area. Likewise, they found an increasing pattern in both those chlorophyll concentrations and SST anomalies in the reproductive area of the hake southern stock, which could have significant implications for that stock's fishery.

Ocean acidification is in part occurring as consequence of the absorption of atmospheric CO_2 produced by human activities, resulting in a global decrease by approximately 0.1 pH unit since the beginning of the Industrial Revolution (IPCC 2012). Likewise, the pH and the solubility of the $CaCO_3$-containing minerals aragonite and calcite are naturally lower at high latitudes and in upwelling areas, where organisms and ecosystems may be relatively more exposed (Feely et al. 2012; Gruber et al. 2012; Hoegh-Guldberg et al. 2014). Carbonate chemistry, and its consequent water acidification, is also expected to be affected by GC with consequences regarding carbonate fixation for exoskeleton formation in mollusks and crustaceans. A reduction in the marine pH level harms the physiology of several invertebrate organisms, especially crustaceans, because that shift reduces the availability of carbonate ions for shell production (Fabry et al. 2008) and also affects both the reproduction and the growth of early life-cycle stages (Long et al. 2017).

The change in surface pH for the 2090s in the Patagonian ecosystem projected from the 1990s (ocean acidification from models under RCP8.5) varies between zones. Whereas for most of the ecosystem the ΔpH value will be less than –0.35, in the northern area (Uruguay) and along the southern coast to the tip of South America, including the Beagle channel, the predicted ΔpH will range between –0.35 and –0.40 (Hoegh-Guldberg et al. 2014). The implications of the projected changes in SST and acidification on the structure and function of oceanic systems and, in turn, in the vulnerability of the Patagonian fisheries are discussed below.

Although in the north-Patagonian gulfs, where the main shellfisheries occur, the predicted change in pH is low (Villafañe et al. this volume), the sensitivity of these species is in general high, not only with respect to the needs for their own growth but also for the species composing their diet. On the other hand, because of a remarkable increase in crustacean populations, including that of the Patagonian shrimp and the squat lobster *Munida gregaria* (Diez et al. 2016), the species composition of the benthic and pelagic communities has been changing in the central-Patagonian shelf and the north-Patagonian gulfs. The change in species assemblages together with the natural variability in traditional resources availability (e.g., bivalves, Narvarte et al. 2011; Soria et al. 2016), in some instances, has put the benthic invertebrate fisheries at risk, making forecasting the continuity of their exploitation difficult. Climate change-related effects – such as alterations in rainfall patterns, winds, Ekman transport, and the current regime (Marengo et al. 2014) – may increase the uncertainty in an already variable and unpredictable system and thus make the overall productivity of benthic communities unforeseeable in the future.

The sustainability of the artisanal king crab fishery accessed in the Beagle channel is particularly threatened by ocean acidification because of the specific characteristics of the area and the impact of the changes in the pH levels on decapods of high latitudes. Particularly in regions with fjords and glaciers, such as the Fuegian archipelago, seawater acidification occurs faster (Fabry et al. 2009), and the melting of glaciers, caused by an increased temperature, produces a greater contribution of freshwater that reduces the ability to neutralize acids (Reisdorph and Mathis 2014).

Anthropic Stressors

Signs of overexploitation have been evidenced for both small ones and large-scale Patagonian fisheries (Table 1). One of the most well-known examples is the Tehuelche-scallop fishery in the San Matías gulf, which was fostered by strong demand for scallops from the foreign markets and thus grew suddenly to reach the highest landings in 1970 before finally collapsing in 1991 (Narvarte et al. 2007; Soria et al. 2016). Since then, sporadic recruitments have enabled short and significantly lower productivity pulses than the previous ones. Likewise, other shellfish resources in the north-Patagonian gulfs have suffered a similar fate in later years due to poor fishery policies, inadequate management schemes, a lack of scientific information, and ineffective controls. The stock of the stripped weakfish *Cynoscion guatucupa* in the Bahía Blanca estuary, captured by artisanal anglers since the 1900s, collapsed between 2000 and 2004, in part as a result of the increase of fishing pressure exerted by an industrial fishing fleet operating in open waters around the estuary (López Cazorla et al. 2014). The most relevant example of overexploitation among all the fisheries reviewed in this chapter is that of the hake southern stock. As a result of an excessive increase in fishing effort, an underreporting of catches, and poor controls, this fishery suffered from severe overfishing during the 1990s that led to a closure in 1999 (Vaz-dos-Santos et al. 2010).

In general, the circumstances that led to an overexploitation of the coastal fisheries of Patagonia conformed a similar pattern. First, a strong demand for certain species triggers the interest of fishermen to take advantage of the opportunity. The market demand could be both international and domestic, the latter being no less influential. For example, the domestic demand coming from an increased Asian population in Buenos Aires and other major cities of the country has been boosting the fishing pressure on invertebrates from north-Patagonian gulfs (snails, crabs, razor clams, geoduck, and other shellfish), in which essential information (biological, ecological, fishery) is practically absent. Second, the environmental policies and fishery-resources management are both deficient at the provincial government level, and in many instances no enforcement or control of the measures is in effect. Therefore, though certain management criteria already exist, the small-scale and artisanal fisheries virtually work on open-access systems, generating high fishing pressures and usually leading to the collapse of the fishing stocks.

Another emblematic example is the mixed king crab fishery in the Beagle channel. The high fishing pressure on *Lithodes santolla* is evident not only from the decrease in its landings over time (Fig. 3E) but also from its population parameters (Table 1). A clear pattern of decline in the abundance has been observed since the commercial fishery began, but also an evident damage of the potential for offspring production (Di Salvatore et al. 2019). In 1994, when the fishery was declared collapsed, the proportion of ovigerous females was only 35% that of the mature females; and, even though the population seemed to have recovered during subsequent years, the abundance dropped again and remained at 28–45% of the original value in the last surveys. In addition, once the capture is on deck and the animals are sorted by sex and size, ovigerous females are returned to the sea, but repetitive capture events generate significant egg losses (Di Salvatore et al. 2019). Therefore, the current scenario suggests that the sustainability of the mixed shellfishery – especially that of *L. santolla* – in the Beagle channel is seriously compromised.

Vulnerability of the Patagonian Fisheries to Global Change

The effects of GC on fisheries will depend on both their specific characteristics and the intensities of the different stressors along with the degree of vulnerability of their components, the natural (e.g., the populations of fishing resources, the biologic communities, the abiotic environment) and human systems (e.g., socioeconomic structure, institutions, governance; Gaines et al. 2019). The identification of the intrinsic elements that make a socioecological system vulnerable to external influences is necessary for designing strategies and public policies to counteract the effects of GC on the ecosystems and consequently on the communities that depend on those resources (Ruano-Chamorro et al. 2018, among others).

Today, research on the effects of GC on the Argentine fisheries is scarce. Only a pair of fisheries recently began to receive attention (Auad and Martos 2012; Marrari et al. 2018; Franco et al. 2020), with only a few small pieces of a huge puzzle having been provisionally fit into place – as, for instance, the effects of GC on meroplanktonic commercial species, discussed in Villafañe et al. (this volume). Particularly for Patagonia, a holistic analysis of the effects of GC on the main fisheries is absent. Nonetheless, from an analysis of the scanty documented pieces of the abiotic, biologic, and human dimensions of the Patagonian fisheries, the impact of specific anthropic stressors (i.e., market forces, overfishing, and its related effects) would, a priori, appear to have constituted the greatest drivers since the beginning of the Patagonian fisheries.

The incidence of stressors related to climate change is not as obvious as that of other, direct, anthropic stressors; this difference may be because anthropic effects have been much more studied to date for the region. Nonetheless, these preliminary insights will be analyzed and discussed in the following sections in light of the information derived from recent studies and cited in other chapters of this book.

The concept of vulnerability has been the subject of studies from different fields of knowledge, such as anthropology, sociology, political science, ecology, geoscience, and engineering. In the example of fisheries, vulnerability analysis has been the subject of research in recent years (Cinner et al. 2012; Ekstrom et al. 2015; Ding et al. 2017; Jara et al. 2020). Although these studies adopted a similar framework to assess vulnerability, all of them involved an analysis of climate-change stressors. Ruano-Chamorro et al. (2018) emphasized the need for using a broader framework, including the stressors of the human dimension, to assess vulnerability to GC.

Beyond the reduced (climate) or broad (global) approach, the vulnerability of fisheries has been assessed as a function of three components: exposure, sensitivity, and adaptive capacity (Ruano-Chamorro et al. 2018; Jara et al. 2020, among others). The exposure is determined by the magnitude, frequency, and duration of the various extrinsic threats that affect the socioecological systems. Sensitivity is the level of intrinsic susceptibility of those systems to the external threats to which they are exposed. Adaptive capacity is the ability of the same systems to modify, absorb, and/or recover from the negative impacts caused by a threat and, further, take advantage of the opportunities that may arise from this recovery. Based on the information from these three components of vulnerability, policy actions should be focused on reducing exposure, minimizing sensitivity, and increasing adaptive capacity.

As was identified in the previous sections, issues related to the human dimension of the GC have been modeling the Patagonian fisheries throughout its history and seem to have a major influence nowadays. The Patagonian coastal societies, however, do not depend exclusively on fishing and have revenues coming from other economic activities (e.g., tourism, livestock, ports, maritime traffic, wind power, oil and gas, mining, industries) as well as state administration. Most of these activities also rely on the marine ecosystem services and sometimes interact with fishing especially when they overlap spatially. Likewise, during recent decades, major marine protected areas have been established, limiting spatially and temporarily the use of ocean space and resources by fishing and other activities.

In summary, the Patagonian coastal fisheries and their related societies and economies configure complex socioecological systems, each with its own particular characteristics (see Sala this volume). Comprehensive conceptual frameworks for the assessment of social and ecologic vulnerability within the context of the socio-ecological systems approach (Binder et al. 2013; Berrouet et al. 2018) provide useful insights on the mechanisms that mediate vulnerability and the role of governance to promote adaptive action and resilience. This kind of framework, likewise, incorporates the governance-related variables and considers the differences in beneficiary profiles in the social vulnerability analysis.

In the example of the Patagonian coastal fisheries, a complete study of vulnerability to GC will require a specific analysis that should take into account a broader perspective and incorporate a great number of variables related to the ecologic and social aspects. Although such a study is beyond the scope of this chapter, in the next section we will perform a preliminary appraisal to identify and discuss the main stressors of GC affecting the Patagonian fisheries.

Ad Hoc Assessment of the Vulnerability of the Patagonian Fisheries to Global Change

An analysis of the vulnerability of a socioecological system to GC is a key element for ensuring healthy, sustainable fisheries in the future. In this section, we use an ad hoc framework for examining the vulnerability of Patagonian fisheries, owing to a facile application to fishery data that are poor in comparison to those of fisheries with robust assessments (e.g., involving long-term series of survey data, data-rich stock assessments, published literature for which multiple methods are used). The vulnerability of Patagonian fisheries to GC is analyzed here concerning the most evident physicochemical (increasing water temperature [WT] and ocean acidification [OA]) and anthropic (overexploitation [OE] and market forces [MF]) stressors. Exposure, sensitivity, and adaptive capacity were rated as low, medium, or high for each stressor (Table 2). In the instance of the WT and OA, the three categories were established on the basis of the data reported by the International Panel of Climate Change (IPCC) (Hoegh-Guldberg et al. 2014) for SST and pH (those observed and from models). For anthropic stressors, ad hoc criteria were adopted for the OE

Table 2 Criteria considered to qualify the different dimensions of the vulnerability of the Patagonian fisheries to both natural (increasing water temperature and acidification) and human (overexploitation and market forces) stressors

Dimension	Stressor	Criteria	Rate
Exposure	WT	The SST increase in the ecosystem of the fishery has been negligible over the past six decades (IPCC SST Index <0.75 °C)	L
		The SST increase in the ecosystem of the fishery has been moderate over the past six decades (0.75°C < IPCC Index < 1.25 °C)	M
		The SST increase in the ecosystem of the fishery has been high over the past six decades (IPCC Index >1.25 °C)	H
	OA	The ocean acidification in the ecosystem of the fishery is low (IPCC Δ surface pH <–0.35)	L
		The ocean acidification in the ecosystem of the fishery is moderate (-0.35< IPCC Δ surface pH <–0.4)	M
		The ocean acidification in the ecosystem of the fishery is high (IPCC Δ surface pH >–0.4)	H
	OE	Fishery managed under EAF, ITQs, and long-term scientific guidance	L
		Fishery managed under an olympic system with basic scientific guidance	M
		Fishery works as an open access scheme with scarce or null scientific guidance or management	H
	MF	Fish products are in high demand and both sold in the domestic market and exported; demand and prices are sustained	L
		Fish products are in high demand and both sold in the domestic market and exported; demand and prices are highly variable	M
		Most of the fish products are exported; demand and prices are highly variable	H

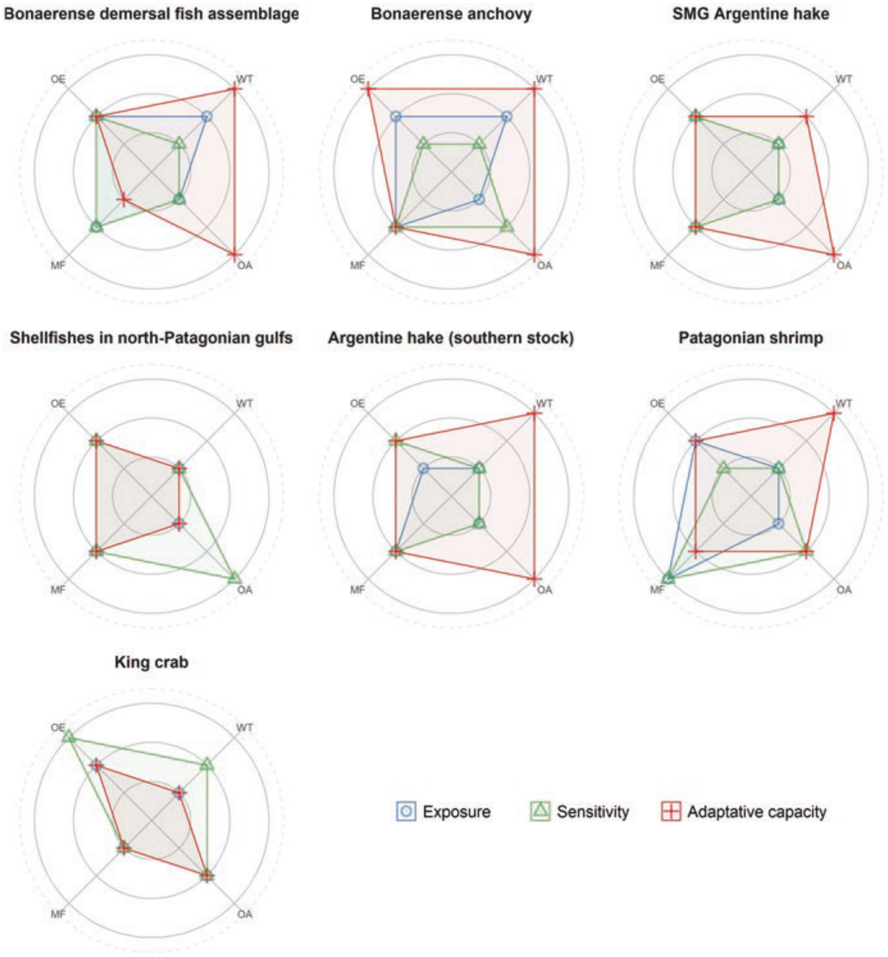
(continued)

Table 2 (continued)

Dimension	Stressor	Criteria	Rate
Sensitivity	WT	Target species manifest high tolerance to thermal variations	L
		Target species manifest medium tolerance to thermal variations	M
		Target species manifest low tolerance to thermal variations	H
	OA	Target species are insensitive taxa to acidification and are not dependent on food-sensitive taxa	L
		The target species are somewhat sensitive to acidification or dependent on sensitive taxa	M
		The target species are sensitive to acidification or highly dependent on sensitive taxa	H
	OE	Fishery is sustained by surplus and/or highly productive stocks	L
		Fishery is based on medium or long-lived species and exploited at maximum sustainable yield	M
		Fishery is mostly sustained by low abundance, long-lived, and low-fecundity species or by species with sporadic and/or uncertain recruitment	H
	MF	Fish products are in high demand, and no substitutes are known in domestic and export markets	L
		Demand for fish products is stable, but other similar products compete both in domestic and export markets	M
		Fish products are mostly exported, demand is variable, and other similar products compete	H
Adaptive capacity	WT	The fishery depends on the site and has limited mobility	L
		The fishery depends on the site, but it is highly mobile	M
		The fishery is highly mobile and does not depend on any site	H
	OA	The fishery is mono- or multispecific and depends (directly or indirectly) on target species sensitive to acidification	L
		The fishery is mono- or multispecific and depends on a few target species sensitive to acidification	M
		The fishery is mono- or multispecific and does not depend on any target species sensitive to acidification	H
	OE	Fishery lacks management and scientific advising; controls are weak or null	L
		Management and controls are state-centralized, no formal managements plans exist, and some level of scientific advice occurs	M
		Fishery management is proactive and conducted under the EAF principles, management plans, and scientific advice	H
	MF	Fishing sector is weak and lacks infrastructure, organization, and planning	L
		Fishing sector and infrastructure are developed with production based on commodities or some added value	M
		Fishing sector is organized, and human resources are innovative. Production is diversified and either based on added value or certified	H

Abbreviations: *WT* water temperature, *OA* ocean acidification, *OE* overexploitation, *MF* market forces, *SST* sea surface temperature, *IPCC* Intergovernmental Panel on Climate Change, *EAF* Ecosystem Approach to Fisheries. Each attribute was scored on a three-point scale indicating low (L), medium (M), and high (H) values at which each criterion operates regarding different aspects of fishing management: we assessed the system of access to the fishery (open access, olympic fishing, or property rights-based schemes, i.e., ITQs), the level of scientific advice, and the level of adoption and/or implementation of formal management plans from an ecosystem perspective. For MF, we explored the dependence of the fishing of external and/or domestic markets, the existence of substitutes and/or competing products, the stability of the demand and the prices, the type of fish products (commodities or added value), and the level of sectorial organization and infrastructure of the fishing sector (Table 2).

An analysis of the vulnerability to climate-change stressors (Fig. 4) indicated that most of the Patagonian fisheries have been subsisting in a scenario of low



Bonaerense demersal fish assemblage

Bonaerense anchovy

SMG Argentine hake

Shellfishes in north-Patagonian gulfs

Argentine hake (southern stock)

Patagonian shrimp

King crab

Fig. 4 Radar charts for comparisons of vulnerability of the Atlantic Patagonian fisheries. The colored polygon represents each of the three dimensions of vulnerability (exposure, sensitivity, and adaptive capacity) according to the different stressors of global change evaluated (*WT*, water temperature; *OA*, ocean acidification; *OE*, overexploitation; and *MF*, market forces). The perimeters represent the increasing rankings from the center to the perimeter of each dimension assessed (*L*, low; *M*, medium; and *H*, high) exposure to climate change (WT and OA). Fisheries located at the geographic extremes of the Patagonian shelf, however, i.e., the Bonaerense anchovy and Bonaerense demersal fish assemblage and the king crab fishery in the Beagle channel, were recognized as moderately exposed to WT and OA, respectively (Fig. 4). Regarding the exposure to the anthropic stressors (OE and MF), most of the Patagonian fisheries were categorized as moderately exposed, and only one exhibited a high exposure, namely, the Patagonian-shrimp fishery, which appeared to be highly exposed to market forces. In contrast, OE appeared as the most serious threat to the other fisheries. This level of exposure to OE is due to the prevalence of management based on olympic schemes and a lack of formal management plans.

As to the sensitivity to the environmental stressors, the Patagonian fisheries generally displayed low and moderate scores, with the shellfishery in the north-Patagonian gulfs being classified as highly sensitive. This fishery involves the species that are highly sensitive to OA, both directly and indirectly, as their feeding resources may also be affected by both OA and WT. The Patagonian shrimp and king crab fisheries were identified as moderately sensitive to OA and the latter also to WT. The anchovy fishery is considered moderately sensitive to OA due the possible negative effects of low pH levels on the visual system of their larval stages (Miranda et al. 2020) as well as indirectly through the productivity of its main preys (copepods). With respect to sensitivity to anthropic stressors, the Patagonian fisheries had mostly moderate scores, and only two were identified as highly sensitive (the southern king crab fishery to OE and the Patagonian shrimp fishery to MF). While shrimp prices are unstable and substitute products are present in the domestic market that likewise compete in the international market, the king crab presents low abundance and low fecundity (Table 1) making the species highly sensitive to OE. Finally, the invertebrate fisheries of the Patagonian gulfs underwent a boom-and-bust history for most of the target species involved, thus resulting in a high variability in their production, as a consequence both of sporadic recruitments (e.g., scallops and mussels) and the exploitation based on long-lived species (e.g., three clam species). The exploitation directed at single-cohort beds, with the management based on the idea of "taking every organism before it dies," is a clear sign of the thoughtless situation. In addition, these fisheries have neither general formal management plans nor strong regular technical advice.

With respect to the adaptive capacity of the Patagonian fisheries in the face of WT and OA, five (those of the multispecies and the anchovy at El Rincón, the hake southern stock, the shrimp, and the San Matías gulf hake) had high-moderate scores, and two (the shellfisheries in the north-Patagonian gulfs and the king crab fishery) had a low score. The low scores of the last two can be explained by the almost null mobility of the fleet, represented by small boats that operate on only a daily basis, with very limited autonomy. By contrast, fisheries involving industrial development can follow the movement of the target species when migrating as consequence of environmental stressors. As to the anthropic stressors, two fisheries, those of the mixed king crab in the Beagle channel and the demersal fishes off the Buenos Aires province, scored at a low adaptive capacity, mainly as a result of market forces since the management of the fishery is weak, without infrastructure and organization, or the fishery operates opportunistically with low added value production. Nevertheless, most of the fisheries fall in the moderate category in the face of adaptive capacity to OE because of the absence of formal management plans, a moderate organization of the sector, and low added value to the fishery products. The schemes of centralized management prevail, with some degree of scientific advice and a certain level of organization, but the production continues to be based on commodities. The anchovy fishery, owing to its status of underexploitation, is the only one with a high adaptive capacity.

Our approach, although essentially qualitative and preliminary, provides a means of understanding and visualizing how the key dimensions of vulnerability vary both within and among fisheries. In view of the relatively low predicted changes in temperature and acidification in the Patagonian coastal ecosystem region, the fisheries operating in this realm appear to be low or moderately exposed to the environmental stressors of GC. The shellfisheries of the north-Patagonian gulfs, however, which appear to be highly sensitive to OA, could be threatened by that stressor because of the low adaptive capacity in the face of this problem. This fishery, as well as that of the mixed king crab in the Beagle channel, manifests a low adaptive capacity as a result of the profile of the artisanal fleets and gear used that restricts the ability of the fishers to follow changes in the distribution of the targeted species. In contrast, the remaining fisheries, with a fleet mainly composed of vessels capable of operating at longer distances from ports, can adjust to shifts in the distribution of resource resulting from climate drivers. Finally, it must be clarified that in the previous analysis, we only focused on the direct effects of the environmental stressors. Those factors acting indirectly on early stages, as well as other, such as changes in radiation, deoxygenation, and invasive species, could also affect the availability of resources; thus fisheries could be affected by several hindered causes.

As explained in the introduction, the market forces in combination with overfishing have been strong historical drivers in the performance of the Patagonian fisheries. OE – for example, of the scallop in north-Patagonian gulfs, the mixed king crab in Beagle channel, and the hake southern stock – has been fostered at different times by external market pressure. Nonetheless, whereas overexploitation could be partially controlled and reverted through legislation and management, the effects of the market forces cannot be regulated in the same way.

In Patagonia, since fish production is mostly exported, the dependence on external markets will always be a problem. Moreover, even though technical measures based on competent scientific advice can contribute to the avoidance of OE, the management system will continue to be the key driving element to be improved. With the exception of the hake southern stock, all the coastal fisheries are still managed under the olympic system, and a worrisome example is that targeting the Patagonian shrimp. This fishery, the most significant from an economic and social point of view, is managed through "catch authorizations". Uncertainty about the distribution, abundance, and some ecological issues of the resource are argued as reasons that impede the establishment of the annual allowable catch as the basis for ITQ's determinations. Moreover, the management scheme, enacted in 2018 by the Federal Fisheries Council (CFP, by their acronym in Spanish) to regulate the shrimp fishery, considers the positive trend in annual landings a reason to expand "catch authorizations" – but lacks specific measures to reduce effort in the event of negative patterns, therefore promoting an expansion of the fishing capacity that is very far from a precautionary measure.

How to Make the Patagonian Fisheries Less Vulnerable to Global Change

The previous analyses clearly demonstrate that the human stressors of GC have had, and will have in the future, a relevant impact on the performance of the Patagonian fisheries. Therefore, if the fisheries are to survive, their management should have a strategic vision to effectively deal with these influences. The Ecosystem Approach to Fisheries (EAF), and its operational framework, is a comprehensive management scheme spanning coastal and marine areas and their natural resources that promotes a conservation and sustainable use of the whole ecosystem (Garcia et al. 2003). The EAF is a broader concept that considers the impact of the environment on fishing, the influence of fishing on the environment, and the socioeconomic benefits that can be gained from fishing and postharvest activities (Staples and Funge-Smith 2009). The EAF furthermore considers both the knowledge and the uncertainties about the biotic, abiotic, and human components of ecosystems and their interactions (Garcia et al. 2003).

The most significant reform that is needed to achieve the potential of the EAF is a shift in the paradigm of the policy from one that is *production-oriented* to one that is *benefits-oriented* (social and economic; Staples and Funge-Smith 2009), indeed, one that focuses on environmental and human well-being and sustainability rather than the gross domestic product. The potential of the EAF as a conceptual and operational framework to achieve the sustainable management of fisheries involves two key issues: the active role of the stakeholders in the decision-making process and the inclusion of economic and social considerations.

A legal framework has historically been the key tool for the implementation of the fishing policies in Argentina. In the first stage (1967–1997), legislation created the conditions for the development of the fishing sector, and later, with the enforcement of the Federal Fishing Act, those policies served to correct the undesired effects of the huge development that resulted. Therefore, the adoption and implementation of the EAF in Argentine fisheries will require a site-specific legal framework to generate the appropriate incentives according to this paradigm and the different issues of the fishery policy agenda.

The active stakeholder participation in the Argentine ITQ process was crucial to avoid conflicts related to that new management scheme (Bertolotti et al. 2016). The experience gathered worldwide on the implementation of the EAF (Staples and Funge-Smith 2009) emphasizes the importance of both stakeholder participation and the need to review and adapt existing legal instruments and practices that impact fisheries, including the cross-sectoral relationships (for instance, tourism and coastal development).

During the first decade of attempts to implement the EAF, many countries and regional organizations made essential advances (Pitcher et al. 2009) with tangible evidence of a nascent transition (i.e., the establishment of the northwest Atlantic fisheries organization) from the traditional single-species management toward the EAF goal (Koen-Alonso et al. 2019, and references therein). In Argentina, the term *ecosystem approach*, as an indication of the desire to introduce an ecosystem perspective to fishery management, has been included at the highest level of official documents of the CFP since 2003 (CFP 2020b). The term has been specifically mentioned in the National Plans of Actions for the conservation of chondrichthyans, mammals, turtles, and seabirds, within the context of the Food and Agriculture Organization Code of Conduct for Responsible Fishing. In addition, the need for an ecosystem approach in the marine fisheries research policy was defined by the CFP as "… based on the statements of the code of conduct for responsible fisheries and the ecosystem approach for achieving explicitly formulated objectives, through a multidisciplinary research strategy based on scientific knowledge" (CFP 2012). Thus, references to the ecosystem approach in the federal fishing policy to date have been restricted to both conservation and research issues, whereas the elements related to the human dimension (e.g., stakeholder participation, economic aspects, fishing management, and control) have not yet been considered.

As to the Patagonian fisheries under provincial administrations, the only instance of the EAF adoption was in the Río Negro province in 2010, through the enactment of one specific resolution aimed at establishing the procedure to develop ecosystem fisheries management plans and experimental fishing in the San Matías gulf (BOPRN 2010). This legal framework resulted from a 5-year process of active public participation with stakeholders – through training, workshops, and institutional meetings – funded by the Argentine Ministry of Science, Technology, and Innovation (Ministerio de Ciencia, Tecnología e Innovación) and the Ministry of Production of the Río Negro province (Ministerio de Producción y Agroindustria de la Provincia de Río Negro; ECOPES 2010). Although the legal adoption of the EAF was truly a milestone, the successive authorities since 2012 have nonetheless been deferring its effective implementation.

In conclusion, 20 years after the EAF was first proposed in Argentina, this paradigm still remains but a distant utopia. Moreover, the EAF was not explicitly adopted in the national fishery policy, and the term *ecosystem approach* is usually used to express an implicit desire in this regard, without achieving any progress in incorporating ecosystem objectives into the formal management of the fisheries. Since in Argentina the objectives of fishing policy have always been achieved by an adequate legal framework, a more specific legislation will be needed with undoubtfully to advance toward the effective adoption and implementation of the EAF in the future. Meanwhile, until this legal framework is fully developed, progress could be made with some preparatory actions in order to improve the sustainability of Patagonian fisheries. In this sense, considering the best practices in fisheries management worldwide and the issues of vulnerability resulting from our analysis, a series of priority recommendations are suggested for each fishery (Table 3).

Table 3 Research and management actions as derived from the vulnerability analysis for each Patagonian coastal fishery. The priority level is expressed as high (H), moderate (M), or low (L)

Predicted global change impacts on fisheries	Expected changes	Research actions / management measures	Bonaer. fish assembl. fishery	Bonaer. anchovy fishery	SMG-hake fishery	Shell-fisheries in north-Patag. gulfs	Patag. shrimp fishery	South. stock hake fishery	King crab fishery
Climate change	In species distribution and composition due to temperature increase	Support research on habitat use/spatial distribution model Create and maintain long-term programs to monitoring environmental variables Identify and monitor indicators of changes and trends in species composition	H	M	L	M	M	M	M
	In productivity of stocks due to acidification	Update studies on diet, growth, and population dynamics of key species Assess the effects of environmental stressors on key species through experimental studies	M	H	L	H	M	**L**	H

Anthropogenic changes	Increase of fishing pressure	Establish ITQ (or other property rights-based scheme) into the legal framework Adopt and enforce management plans under EAF principles into the legal framework Promote training and coaching in public participation processes Improve scientific and technical capacities in stock assessment in local institutions	H	L	H	H	H	M	H
	Increase of seafood demand	Support research and development in seafood technology Promote the diversification of the portfolio of seafood products Promote the production of local added value in the local seafood industries	H	L	H	H	L	H	L

Conclusions

No strong evidence of relevant effects of the physicochemical stressors of GC on the Patagonian fisheries has been found, but increasing temperature and acidification (and their cascade effects such as algal blooms including red tides, changes in species distribution – also for invasive ones) could be a threat mainly for small-scale fisheries targeting shellfish both in the north-Patagonian gulfs and the Beagle channel. The southward expansion of the subtropical gyre and the Brazilian current, as well as the variation in the wind pattern in the northern area of the Patagonian shelf – which alteration could affect the water mass north-to-south advection – could affect the seasonal northward extension of Magellanic resources associated with cold and salty waters. Likewise, SST changes could also have a significant effect on the recruitment dynamics of the hake southern stock. In addition, the very important plausible effects of climate change on early stages of the main fishing resources are practically unassessed, and this is a significant gap.

The effects of human stressors are more evident if the analysis is performed over the history of the Patagonian fisheries. In general, the development of the Argentine fishing sector reflects the globalization that took place since World War II. The first stages of this process revealed, gradually, the expansion of geographic, bathymetric, and taxonomic boundaries (*sensu* Pauly 2009) as well as the consequences derived from inappropriate management systems that were conducive to overexploitation of many fish and shellfish resources.

The evolution and modernization of the federal legal framework has enabled the reduction of the negative effects of overexploitation for the larger-scale fisheries. Nevertheless, with the exception of the southern-stock hake fishery, which, owing to its migratory nature, has been included under the federal quota system, the remaining coastal fisheries of Patagonia continue to be managed through olympic fishing schemes, with both internal and opportunistic external market being the main drivers of their vulnerability.

The effects of ocean warming and acidification on primary productivity, nutrient cycles, the global distribution and survival of marine organisms, and thus the amount and type of fishing resources (which will be affected both directly and indirectly) are just a few examples of the gaps in our knowledge that could be critical for adapting to GC. The sustainability of fisheries therefore depends on the adoption of effective legislation and informed management incorporating the concept of an ecosystem approach to fisheries.

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The Future of Atlantic Patagonia: On Urban Planning and Prospective Toward the End of the Anthropocene?

Diego Capandeguy and Thomas Sprechmann

Atlantic Coast of Patagonia Analyzed from Urban Planning

The Atlantic coast of Patagonia stretches over more than 3,000 kilometers at the southern end of South America. It expands from the mouth of the Colorado river in the north to near Cape Horn in the south. It is a unique coastline, a vastness with few cities, low human population density, great distances, and large natural spaces. This is part of an abstract organization of the great territory. Boundaries between Argentinean provinces themselves evidence a "modern" anthropic pattern of territory possession. Such arbitrary territorial organization translates in the configuration of the large Patagonian ranches (*estancias*), especially in Tierra del Fuego, divided according to a regular grid. Patagonia is more than the great southern geography of the American continent. It is the land of its people, but it is also an aggregate of imaginary and local, regional, national, and global representations (Schneier-Madanes 1996; Blanco 2009).

This chapter focuses on the Atlantic Patagonia, on different qualitative matters deemed as substantive from a present urbanistic perspective. What does this urbanistic gaze mean? Urbanism refers essentially to the localization of human activities, to the primary architectural and infrastructural format and landscape management. Urban planning (urbanism) transcends city-centered visions. Correa (2018) speaks of an "urbanism beyond the city" with respect to extractive settlements in South America, which also applies to the Atlantic Patagonia. Urban and regional planning is essentially a political, social, and cultural practice.

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Below, four territorial approximations to the Atlantic Patagonian coast are addressed, construed as:

- Land-sea strip with human settlements concentrated within the vastness.
- Complex and fluctuating territorialities according to a field condition.
- Mosaic of phenomenological landscapes.
- Captive environment within viscous hyperobjects.

Each of these approaches involves different conceptual bases and has operational implications in urbanistic practices and in territory management. Such approaches affirm this oceanic coast as part of the broad territoriality of Patagonia. This is conceived as a Global Garden (Sprechmann and Capandeguy 2006), not as a distant or peripheral region of the planet, as it will develop later.

Land-Sea Strip with Human Settlements Concentrated Within the Vastness

A possible substantive characterization of this extensive seaboard would be that of a coastal strip, of variable width, including sea and land parts, with their interfaces, and human settlements, the latter being scarce and sparsely populated as compared to the vastness of Patagonia (Zaixso et al. 2016). The Patagonian coast constitutes an interrelated southern territoriality with the Chilean vicinity and with the Malvinas islands.

Only part of the environments with great biodiversity on the coast constitutes Protected Natural Areas (PNA), in the national or provincial jurisdiction. Such coastal PNA were created in accordance with different environmental conceptions than those of the first generation of Andean National Parks and with less public funding. The latter were closely associated to the nineteenth-century picturesqueness-naturalist conception of Perito Moreno or the Bustillo brothers (Silvestri 2011). Among the areas created in Argentina's Patagonian coast, there are more recent and dissimilar cases, from the Península Valdés Provincial Nature Reserve, declared World Heritage Site by the UNESCO. Also noteworthy are the recent interjurisdictional parks between the federal and provincial governments. It is the case of Patagonia Austral Interjurisdictional Coastal Marine Park in Chubut, Isla Pingüino Interjurisdictional Marine Park and Makenke Interjurisdictional Marine Park, both in Santa Cruz, which are part of an ecosystem and relational approach (Caille et al. 2013). Finally, Monte León National Park is a special case, since it was acquired by the conservationist tycoon Tompkins, then recovered and donated to the federal government. Likewise, the Islote Lobos National Park is in process of formation, on the San Matías gulf. Why include such Natural Protected Areas in this urbanistic perspective? Because the majority of PNA, apart from their conservation objectives, are means of tourist-urbanistic attraction. In addition, the areas surrounding PNA may also be sought for residence and tourism.

The human settlements are a few towns and cities, all of them recent, considering the more extensive urbanizing cycle of South America. This Atlantic Patagonia, interpreted as a coastal strip of vast, highly biodiverse environments and of concentrated human settlements that are far apart, is articulated by means of the coastline, by National Route 3, and crucial infrastructure such as gas and oil pipelines, electric energy networks of hydroelectric or wind origin, and canals with many local ramifications bringing water for human consumption. The main ports and infrastructural networks were built for export primary resources to the main populated and rich cities located in the Pampas core or to other countries. Therefore, Patagonia can be considered as a region – commodity (Daher 2003) – without prejudice to its ecological and tourist or scenic values. Within this land-sea strip, one part has been interpreted as a development belt, including the so-called beaches corridor. They are singular visions, more programmatic than real, due to the great interregional distances and their usage patterns. Therefore, the Atlantic Patagonia is a complex strip in a vastness stressed by human action. National and provincial administrative limits, ecological zones, PNA, infrastructures, and energyscapes are superimposed on this territory. Its relation with respect to other areas of Patagonia and the Southern Cone is understood to be relevant (Fig. 1).

Complex and Fluctuating Territoriality According to a Field Condition

Towns and cities in Patagonia have been interpreted within urban systems and subsystems based on their relative Patagonian proximity (great distances from a European perspective), interregional flows, and complementation of equipment and services (Roccatagliata 1992, 2008; Subsecretaría de Planificación de la Inversión Pública 2015). These urban systems could be viewed as a type of urban archipelagos, following Soja (2008).

Atlantic Patagonia could also be considered, from an urbanistic standpoint, as an aggregation of vast territorialities with different field conditions, not stable but fluctuating: "… a field condition could be any formal or spatial matrix capable of unifying diverse elements while respecting the identity of each one of them. Field configurations are loosely bounded aggregates joined in a flexible fashion which are characterized by their internal porosity and connectivity …" (Allen 2009).

Hypothetically, and based on field conditions, productive fields may be recognized (oil and wind energy, even fisheries), PNA, unguarded rustic rural areas, urban settlements, and some marine areas. This conception of complex, fluctuating territorialities is more open than the widespread notion of regions and micro-regions from the second half of the twentieth century. And it is more plausible with the material logic of the present global cycle of capitalism.

There are some coastal territorialities with clear, unitary field conditions of diffuse limits within Atlantic Patagonia, which are to be highlighted, such as:

Fig. 1 Atlantic Patagonia. Thematic map of territorialities highlighting the complexity of the coastal strip, ecological zones, the most important Natural Protected Areas, network of cities and urban territorialities, infrastructures, energyscapes, field conditions, and relationships with the rest of Patagonia, the Southern Cone, and the South Atlantic. (Original design by Sprechmann and Capandeguy, redrawn by Sosa and Walasek in 2020)

(a) The territoriality with field conditions of San Matías gulf, in the land-sea interface to the west and north of the gulf. It comprehends the San Antonio bay PNA and other provincial PNAs on the coastline, several cities like San Antonio Oeste and Las Grutas, a subfield in itself. How to interpret the territoriality with field conditions of the lower valley of the Negro river, the cities of Viedma and Carmen de Patagones, and El Cóndor is an open issue.
(b) The territoriality with field conditions of the Valdés peninsula, with its PNA, perhaps Nuevo gulf and Punta Tombo Marine Protected Area, the triad of cities Puerto Madryn-Rawson-Trelew and the old town of Gaiman, and the recently built wind farms.
(c) The territoriality with field conditions of Comodoro Rivadavia, which includes this city and the group of inland and offshore hydrocarbon formations being exploited in San Jorge gulf, settlements like Caleta Olivia and Puerto Deseado, among others, and many wind farms. An open question is whether to include the Patagonia Austral Interjurisdictional Coastal Marine Park. It is the most complex territoriality in the Patagonian coast interpreted in terms of fluctuating field conditions, which transcends different state jurisdictions.
(d) A particular case is that of the Tierra del Fuego archipelago, with its curious situation of provincial and national borders both dry and projecting into the ocean, and its global geopolitical position. This territoriality includes Tierra del Fuego island, Magellan strait, and the Tierra del Fuego channels, even distant De los Estados island, and the Argentinean cities of Ushuaia and Río Grande and the Chilean cities of Punta Arenas and the small Puerto Williams.

Mosaic of Phenomenological Landscapes

The coastal landscape of Patagonia permits various approaches. One of them is that of landscape ecology. The coast under analysis is mostly part of the Patagonian Steppe Ecoregion and of the Oceanic Coasts Ecoregion (Argentine sea). Only one section in the north forms part of the wider Hawthorn Ecoregion. To the south, in Tierra del Fuego, the coast is a part of the Subantarctic Woods Ecoregion or Patagonian Woods (Godoy et al. 2007; Morello et al. 2012).

Another register is the sociocultural approximation of the landscape. In this regard, all of Patagonia, not only its Atlantic coast, makes it possible to appreciate a set of charismatic landscapes, many of them sublime. These are linked to a specific setting and place as a highlight (Capandeguy 2015). In the coastal area, charismatic landscapes are not as clear as in the Andes. Among them, we can find the Valdés peninsula, especially Nuevo gulf and the sightings of southern right whales; the recognizable formation of Monte León National Park; some scenery in Ushuaia; or Cape Horn, with its lighthouse in Chile. Naturally, the recognition – and symbolic invention – of such charismatic landscapes is different for a tourist or for a Patagonian habitant.

On the Atlantic coast of Patagonia micro landscapes of diverse character and format may be appreciated, with a strong locational matrix. One aspect is that of micro landscapes with high naturalness, like the meteor-formed sandbars and the odd unspoiled warm water beaches (like Rosas bay or Perdices point, both into San Matías gulf). Another aspect would be that of rural micro landscapes, such as Estancia Harberton in Tierra del Fuego, or the ports, or inland and offshore oil fields and the wind farms that have generated geographies of energy (Zimmerer 2013), relatively generic (Kubo 2006).

Nevertheless, the Atlantic coastal area of Patagonia is dominated by discrete landscapes, non-charismatic. This would be the case, among others, of its large steppe expanses, with its hedges, low slopes, and ocean sandbars made visible by the ebbing tides, plus, the rough ocean. Such discrete landscapes could also be interpreted according to the aforesaid theories on field conditions. In line with this, Patagonia has been conceptualized as a geography of scalar entities without graduations between "… the enormity of the desert or the sight of a tiny flower …" (Chatwin and Theroux 1993). In keeping with this, Alys (2006), in the film essay "Patagonia, A Story of Deception," values the mirages of these lands: "… as one walks towards it, the mirage vanishes forever in the line of the horizon, disappointing or constantly averting our progress; inevitably anticipating our footsteps. It is a phenomenon of permanent disappearance, a continuous experience of elusion...." Some phenomenological keys are the perception of horizontality and vastness, the rule of the wind in the form of a dusty film which impregnates and envelopes everything, or the enchantment of the great ocean tides; the contrast between the steppe, with its stunted bushes; the enormous biomass of the relative few species, such as bird colonies and marine and terrestrial mammals, among others; and the sea teeming with life.

Patagonia is a mythical setting charged with travel apprehensions. Careri (2002) values the experience of the nomad, of the traveler, and of transurbance, inherent to native populations. Some names of travelers and scientists are inseparable from the representations of the coastal landscapes of Patagonia and the South Atlantic. It is the case of Darwin and Fitz Roy (1839), Moreno (1879), Bridges (1875), De Agostini (1934), Feruglio (1949) or Chatwin (1977); among others. A very credible regional legend states that Saint-Exupéry, author of *The Little Prince* published in 1943, to draw the boa that swallowed the elephant, was inspired by the shape of Isla de los Pájaros in the Valdés peninsula. In addition, Conway (2005) proposes a suggestive notion, which is that of landscape species. These are the fauna populations inseparable from a physical setting, like Magellanic penguins, southern right whales, or guanacos. These landscape species could be visualized statically as plays on figures against their background or as fields of different intensities, like the shifting formations of flocks of migrating birds, colonies of penguins, or shoals of fish (Allen 2009). Other chronicles are also very phenomenological (Campagna and Lichter 1996; Lichter 1999). This coast is that of Blue Patagonia (Sprechmann and Capandeguy 2006).

Captive Environment Within Viscous Hyperobjects

Patagonia's coast, just like Patagonia as a whole, shares with other wildernesses visible elements which evidence its macrohistory, whether it is landforms or paleontological or archeological traces (see chapters by Isla and Isla, Griffin et al. and Gómez Otero and Svoboda, this volume). Such wildernesses emerge as extensive meaningful spaces. But they are increasingly finite wildernesses affected by human actions in their current Anthropocene phase (Sprechmann and Capandeguy 2017). The Anthropocene is a geohistorical phenomenon, not a geological category: "… neither water nor soil, nor air, nor living things are in the time or space of those who make all that the frame for their actions …" (Latour 2017).

In a recent vision, Patagonia's shoreline could be perceived as part of the hyperobjects to which it is captive to. Morton (2018) coined the notion "… to refer to things that are massively distributed in time and space relative to humans …"; "… hyperobjects are viscous, which means they "stick" to things that are involved with them. They are non-local.…" Morton (2018) identifies some hyperobjects, such as the planets, the biosphere, oil fields, nuclear materials, endurable human manufactures, and global warming, among others.

This captivity or belonging to such hyperobjects is notorious in the Patagonian coast. Consider the oil slicks in the steppe and in the ocean, polystyrene bags that the wind scatters around, global warming, diverse species, and coastal urbanizations (critical in many locations due to high risk of flooding). Or consider radioactive waste – timeless hyperobjects – as could be generated by installing a possible nuclear power plant in the San Matías gulf, as was proposed a few years ago, a regressive initiative apparently canceled (Capandeguy 2017b). Heavy metals in the soil in some areas and in sea animals may also be regarded as hyperobjects; disused, rusty machines and those being used in the extractive, developmentalist cycles of this Patagonian shoreline; or in the ashes carried by the wind of the large Australian wildfires in early 2020. Freshwater, will that not be a great, increasingly scarce hyperobject, unavailable and more coveted in the near future?

Cities, Urbanism, and Coastal Tourism

Recent Urban Agglomerations in the Vastness

The Argentinean part of Patagonia is approximately 1,000,000 km^2 and represents one third of the country's land area. However, only over 2,500,000 people live there, with a positive net growth rate. In the coastal area, population is estimated at 1,000,000 inhabitants, distributed mostly between some cities and towns that sit along >3000 km of coastline (Capandeguy 2015). These are urban agglomerations in the vastness. Rural population is not meaningful on the coast.

For centuries Patagonia was inhabited by various nomadic peoples. In this regard, it is worth referring to Gómez Otero and Svoboda (this volume). On the coast in particular there are traces of such settlements since 13,000 years ago (Cruz and Caracotche 2008). The native people inhabiting these lands were subjected in the nineteenth and early twentieth centuries, only a few members of some communities survived (Bayer 2010; Mases 2010).

Urbanization of Atlantic Patagonia started rather recently, almost at the beginning of the twentieth century. Previously, only the cities of Carmen de Patagones, Viedma, Puerto Madryn, Trelew, and Rawson had been founded and Ushuaia in the far South. Such foundations were meant to consolidate the national state. To those, other productive settlements have been added, ports and tourist towns, juxtaposed, nearby, or far from the above cities.

Few cities have an estimated population > 100,000 inhabitants, like Puerto Madryn, Trelew, Comodoro Rivadavia (the biggest coastal city), and Río Gallegos. Some urban centers and industrial poles are linked to various practices of so-called developmentalism which has intermittently sounded out South America since the 1960s. Cases in point are the port of San Antonio Este; ALPAT, a mega-industry in San Antonio Oeste; Sierra Grande and its once active iron mine, distant from the coast, but with a dock in Punta Colorada; and ports in Caleta Paula, Caleta Olivia, Puerto Deseado, San Julián, or Punta Quilla. Part of the towns and cities between the mouth of the Negro river and the south of the Chubut province constitutes the aforementioned beach corridor, which is a singular territoriality.

These agglomerations are characterized by several features. Their link to the coast is substantial, and it inspires the local imaginaries of their inhabitants and tourists. Its settlement has been nourished by various migrations, with some segments of migrants still poorly integrated (Barelli and Dreidemie 2015). However, in Atlantic Patagonia, the so-called amenity migration, especially international migration, remains relatively low compared to the recognizable phenomena in other areas of the Southern Cone of Latin America (Gosnell and Abrams 2009; Matossian et al. 2014).

Finally, even oil camps and rigs with temporary co-residents, fish-processing vessels sailing the South Atlantic, and even the huge cruisers could be interpreted as sui generis human coastal and sea agglomerations.

Specificities and Urban Challenges

Coastal districts face various recurring challenges. One group of issues springs from the frequent initial urbanizations, or later expansions, in settings of great environmental vulnerability in the face of climate change. Some evidence is the degradation and destruction of dune ridges and cliffs, loss of beaches, and mismanagement of coastal ecosystems, with ecosystem services being reduced. Linked to the above are the supply of water for human consumption, which left a mark on the founding of cities and the first years of urban existence on these coasts; the disposal of sewage and rainwater; and the appropriate removal of solid waste and the management of highly contaminating industrial discharges. Another issue is the compatibility of industrial, fishing, tourism, and residential and recreational coastal activities with each other and with the conservation of highly natural areas. An associated phenomenon is the littoralization of Atlantic Patagonia. This is expressed in the affirmation and growth of coastal urban centers and in extended urbanization along the coast. It is an extended but discontinuous urbanization.

Another group of issues relates to the improvement of social and economic sustainability. Patagonia's coastal districts are not alien to the material organization of the current phase of so-called late-stage capitalism. They exhibit social-territorial dualisms, many with shanty towns. These coastal towns and cities present environmental liabilities too. Brenner, in the studies compiled by Seville (2017), refers to the persistence of an unequal development at a global level, having studied other vast territories equitable to Patagonia. He recognized different ways of spatial reorganization, the destruction of old statist models, and the affirmation of a rescaled backing of public policies and institutional arrangements. In the Patagonian coast, territorial rescalings have been proposed as factual evidence in diverse extractive, logistic, and tourist activities. Examples of this are the management, expansion, and improvement of the main airports, wind farms, even the international recognition that World Heritage Sites represent, and cruise tourism (pre-Covid-19) with international tour operators. In this scenario, interjurisdictional planning of the vast coastal territory and the possibility of Integrated Coastal Management (ICM) appears elusive but desirable (Boscarol et al. 2016).

Tourism and Urbanism: Relational Practices

Tourism in the coastline of Patagonia is a relevant activity, with several specific studies which are worth referring to. Tagliorette et al. (2016) show the diversity of coastal tourist resources, their relationships with urban planning and the great territory, various impacts of tourism, and the restrictions and challenges of public policies. This section will be limited to an urbanistic perspective, highlighting some relational practices and issues between tourism and urban planning. The phenomenon of tourism in the Argentine Patagonian coast was relevant as from the 1950s, but it shot up in the 1990s. It was a late emergence with respect to the Patagonian Andes brand.

Its development has been associated with at least three factors. First, the repositioning of Valdés peninsula as an internationally recognized natural tourist destination, with iconic activities like whale and penguin watching. It was a special case of consideration of tourist potential prior to the creation of a Protected Natural Area (Kuper 2009). Simultaneously, Ushuaia repositioned itself as a natural and cultural tourism product, the city at the end of the world, previous to the Chilean city of Puerto Williams. Second, the construction of different quality airport facilities which enabled access to the above cities and triangulation with El Calafate, doorway to the Perito Moreno glacier and El Chaltén, two national and global products. At any rate, the low demand and the great distances limit flight offers.

Third, the consolidation of a sun-and-beach tourism is oriented to the regional market and limited to the north and central Patagonian coast. Coherently, there emerged coastal towns, predominantly oriented to sun-and-beach tourism. They operate as seasonal agglomerations for enjoyment and temporary vital consumption, not like towns where to be born and die. Some cities operate as condensers of various types of tourism in their vicinity, e.g., Puerto Madryn. In this regard, various political, economic, and social actors were relevant in the tourist positioning of Atlantic Patagonia. A special mention deserves A. Torrejón, who operated as a notable local, in the sense that Gremion (1976) gives to this category.

Significant relational topics between tourism and urbanism in Atlantic Patagonia are the pressure on natural resources (landscape units, fauna habitats, sand dunes, etc.), the predominance of mono-products, high seasonality, the relevance of non-hotel offers, the frequently poor quality of urban developments, and the significance of the real estate sector associated with residential tourism and, therefore, to the opening of developable land and construction. The latter operates as a refuge investment in a country with frequent periods of socioeconomic instability. However, this could also point in other directions. The links between migration, natural amenities, and new extractivism, all of them significant in the Atlantic Patagonia, the international expansion of online marketplace tools (i.e., Airbnb), and the national and global standstill of tourism imposed by the Covid-19 pandemic since the beginning of 2020 open questions about the adaptive capabilities and their effects on the different territorialities under study.

Patagonia in a Post-humanist Vision

The relation of the native inhabitants of Patagonia with nature and its territorialities was different from western worldviews and practices. Briones and Ramos (2016) studied the native collectives by means of their topology, not metrics, observing various juxtapositions in social space. To modern colonization of European origin, the very notion of Patagonia was a stigma imposed from the times of Magellan's trip. This was a terra incognita in which the other was excluded. Later, in the nineteenth century, the presumed invention of the desert was a metaphor, also applied elsewhere, for an imposition on other men, species, and lands (Rodríguez 2010; Grüner 2015). More specifically, also western culture went from the notion of the coast as an emptiness to its invention as from the eighteenth century, as a pregnant wish for landscape (Corbin 1988; Donadieu 2006). This phenomenon of wish for a coast and its possible representation in the residents of contemporary Atlantic Patagonia raises questions and future case studies. Furthermore, in Patagonia, how much do visions associated with modern progress and humanism still take precedence? Notwithstanding, well into the twenty-first century, Patagonia may be conceived from a post-humanist philosophical vision, which allows to weigh its narratives and practices on this territory in a different way. Today, a diversity of visions of a philosophical nature have progressively consolidated themselves that have driven into crisis both the certainties of modern thought and (the ambiguity) of postmodern relativism (see also Sala, this volume).

From a philosophical point of view, the new currents emerging under the label of New Realism share two fundamental ideas: on the one hand, the crisis of the anthropocentrism and humanism of modern culture since the Enlightenment and, on the other hand, the impossibility of determining reality objectively through thought. Sloterdijk (2000) wrote about the taming techniques practiced by human beings, which was misunderstood in its day. The author suggests that human beings must interact on different terms with others, with machines and living things. He said: "… people are beings that take care and protect themselves and, no matter where they live, they create parks around them. City parks, national parks, provincial or state parks, eco-parks –everywhere people must form an opinion on the way to regulate their self-support."

Based on Sloterdijk's blueprint, the various currents constituting the aforementioned New Realism consolidate new forms of conceiving human's relationship with the planet and living beings in general in a post-humanist perspective. It is worth mentioning briefly the contribution of the following relevant thinkers: Marchesini (2002) questions the overvaluation of the intellectual capacities of the human being vis a vis the instincts of non-human beings; Meillassoux (2015), one of the most important inspirations of New Realism, profoundly draws attention to the anthropocentric visions of so-called Philosophical Correlationism (in his book *After Finitude*, he expands the space-time dimension of the real toward the ancestral – archifossile – beyond human experience); Harman (2015), by means of his object-oriented ontology, positions himself as the model of Speculative Realism, one of the most influential movements of New Realism; he conceives the contemporary world as the generator of hybrid realities created by – monstrous – meetings of objects. Speculative Realism enriched the creative potential of architecture, urban planning, and art in multiple directions, imagining a fictional world with no restrictions or barriers (Torres Nadal 2019). In addition, Gabriel (2015) claims that the overall totality is impossible to grasp and that existence appears only in the context of so-called fields of sense. This represents a profound, rich superseding of hegemonic twentieth-century visions.

Finally, Morton (2019) associates the notion of nature to an anthropocentric perspective, distancing the human from the non-human world. He regards nature as something permanent, whether it is the biosphere, mineral strata, urbanized space, or philosophical, mental, and social space. This thinker claims solidarity with non-humans. In addition, Zarka (2016) suggests the inappropriability of the Earth as a fundamental principle for a philosophical refounding. Even the rights of nature are recognized (Gudynas 2015), contemplated in some Latin American laws. These post-humanist perspectives challenge and could nurture individual sensitivities and that of collectives, multiscalar, geopolitical narratives and practices of various actors, and disciplinary approximations of Patagonia, particularly its Atlantic coastline.

Coastal Territorialities Prospectively

Foresight, as rigid anticipation, has a limited value in times of intense civilizing changes, accelerations, and global disruptions of the Anthropocene. This places human beings at a complex crossroads. Earth is a new battlefield beyond good and bad or divine transcendence (Sloterdijk 2016). All the same, some qualitative prospective hypotheses regarding Atlantic Patagonia will be shared below from an urbanistic approach. Its aim is to facilitate the analysis of future situations with a view to imagining and anticipating proposals of varying verisimilitude, clarifying trajectories and becoming stronger.

Prospective scenarios refer to a set of phenomena that are consistent and considered possible. For each of them, their strongest features will be briefly described, together with some imaginary logic of action of the actors at a territorial level. Naturally, these gazes, which prioritize the territory and the landscape as fields of action, are inscribed in wider political-social, economic, and environmental trajectories. Therefore, they are simplified, amplified situations to be verified, some more plausible, others less (Godet 1993). With respect to planning and prospective, "planning… is an action to order the future with a view to a change from a present situation to an expected one… Conceiving the future is an act of fantastic creation, inherent to Man, it is part of his essence and of its culture" (Martínez Guarino 1991). Below, five prospective scenarios are presented, with a diffuse horizon of three decades.

Inertial Patagonia

In this scenario, the field conditions of the studied territorialities and the current tendencies of littoralization of the coast would be affirmed, especially in the beach corridor; internal tourism will be more important relative to international tourism, and some new residential and nature tourism products are emerging. In parallel, some neoextractivist practices (e.g., fracking) will increase, and a slight economic diversification and urban growth with pressures on nearby ecological infrastructure will continue (Capandeguy 2017a). Global warming will affect road infrastructure and some coastal first rows, whose effects will be belatedly and softly mitigated by *ex post* actions and by the so-called climate change adaptation programs. Natural Protected Areas and a somewhat more consistent coast management will probably increase. The influence of civil society would also grow in connection with various environmental improvements and for the rejection of mega initiatives of high environmental risk which might arise periodically.

Rescalated Patagonia of Global Geopolitical Affirmation

Patagonia may assume a strategic role as a hub in a scenario where China has greater global gravitation on the South Atlantic and on Antarctica. The Magellan strait will once again have a global geopolitical role as an interoceanic crossing. In Antarctica, neoextractivist prospections would be initiated with some international controversies or disputes. Various mega ventures would be located on the Patagonian coast in the fields of energy, logistical, services, and maybe food post-industry. These would fundamentally generate an increase in environmental risks, new focal highly qualified jobs, and certain divisions of the imaginaries of local coast societies. Also, it will increase migration in search of employment opportunities and ecosystem services, within a more diverse and multifunctional coastal landscape.

Patagonia Strenghthened in Local and Regional Achievements

It would be a scenario with an affirmation of the local and regional initiatives in all of Argentine Patagonia. The territorial development scene would be different (Arocena and Marsiglia 2017). The national and provincial state, local bourgeoisie, and some communities of natives would reach some agreements. That would imply a strengthening of regional or subregional adaptive governance, with greater relative importance of Patagonian actors. That will be reflected in a diversified, not so opaque socio-territorial *milieu* and in the arduous, disputed achievement of greater autonomy. Outlined coastal territorialities would be more complex. They would generate dual initiatives; development projects would increase, as would transparent public revenue clawback and ecological management on the coast. The affirmation of this scenario could have positive effects.

Non-human Disruptive Patagonia

In this scenario would converge the effects of global warming, the containment or reduction of human growth, and new forms of artificial intelligence, even hybridized with other species, humans included. Cyborgs or other replicants (Diéguez 2016)? The human species would accept its coexistence by default or by sedation. In the face of catastrophic interpretations, would a better ecological coexistence not be achieved? Fictional or plausible scenario that we do not want to visualize?

Cohabited, Less Anthropocentric Patagonia

This scenario is related to the affirmation of the cited post-humanist view with a certain positivity and sense. Greater cohabitations, hybridizations, and changes in the collective and individual sensibilities would be experienced, the notion of an ecological economy taking precedence. Highly natural territories, like Atlantic Patagonia, would assume a special value. That would be associated with greater global and local effectivity in reducing global warming and the consequences already underway. In that regard, some adaptive changes in coastal areas would be proactively agreed upon. Human beings would accept the limits of their dominant practices in the Anthropocene. Braidotti (2015) refers to a post-human continuum with an affirmative latency, highlighting the relationships and encounters between humans, non-human species, and technologies. Perhaps, biological intelligence units will increase which may transform solar radiation into oxygen and biomass, resulting in a symbiotic architecture and urbanism. This is visualized as a desirable yet unlikely scenario, but not so utopic.

The above scenarios cannot be chosen, but they may be wished for and the human being may attempt to get closer to them. Perhaps future scenarios will be mixed or there will be others. This exploration of futures for Atlantic Patagonia is inseparable from the cultural changes, from the sensitivity changes, and from the paradigms under transformation and in emergency nowadays. The above scenarios seem to perpetuate the Anthropocene, or they pose their possible end in various keys. The last scenario, that of a cohabited and less anthropocentric Patagonia, refers to a possible end or change of the Anthropocene according to a vital positivity. In this regard, Sloterdijk (2016), from his philosophical perspective, underlines the necessary cooperation, between different ways of life, to achieve a co-immunity.

Urbanistic Explorations Toward Other Futures

The shift toward post-humanism is broad in philosophy, and it is more limited in architecture and urbanism. This discipline seems to move between two extreme positions. On the one hand, there is vindication of the autonomy of architecture, with projects and theoretical reflection as a resistance to the established (Aureli 2008). On the other hand, there are positions that evidence from a syncretic amplitude (Zaera Polo 2016) to trans-architectural practices permeated by other approaches. In particular, urban planning is essentially a practical discipline, with a frequent project component. Its objects of study are complex and multiscale, with various transfers and cooperation with other disciplines (Almandoz 2020). At the planetary level, thinkers such as Brenner and Schmid (2015) record new epistemologies of the urban. They recognize concentrated, extended, or differential urbanization processes, as evidenced by the Patagonian coast itself as analyzed in the previous sections. This is not independent of legitimate tensions, bids, and projects of various social actors. In Atlantic Patagonia a modern urbanism dominated.

This was a colonizer, discreet, of frequent little sensitivity with the place and its natural pattern. Currently, this is mixed with a regulatory urban planning (Basualdo 2018) and with specific qualification actions. The new urban planning practices in this region should start from the important biopolitical awareness and ecological sensitivity of its population. In the future, other alternatives may be considered, as will be developed in the following sections.

Patagonia Global Garden: On Extended Territorialities

The coast under study is a part of a wider regional territoriality, Patagonia, the southernmost continental tip of South America and its oceanic vicinity. Patagonia may be interpreted as a unitary global territoriality, as a Global Garden. In effect, Patagonia, Amazonia, North America's Great Woods, Greenland, Siberia, Mongolia, the Sahara, the Savanna and the African Jungle, Australia, the rest of Oceania, and Antarctica have been conceptualized as a repertoire of great Global Gardens: "Global Gardens are the other face of the so-called Global City –in the words of Sassen (1991). All of them are radical territories, of high specificity and of world renown. Both, Global Gardens and Cities, emerge in the last decades. To a certain extent, they are inevitable and have great appeal…" (Sprechmann and Capandeguy 2006). Its parallel with a garden that has been associated with emerging landscape sensitivities since the 1990s (Clément 1999; Corner 1999; Ábalos 2005; Waldheim 2006; Colafranceschi 2007).

The Coastal Patagonian Global Garden is a mix. On the one hand, like any garden, Patagonia possesses an element of treasure, of refuge, as are its vestiges of highly natural life in the form of iconic natural edens valued by conservationists, tourists, and its inhabitants, such as Valdés peninsula or Punta Tombo MPA on the Atlantic Ocean. On the other hand, this giant garden functions as a planetary backyard, with its sites for the exploitation of extractive hydrocarbon and fishery resources significant for world markets, its environmental liabilities, or the modern and bloodless slaughter of other species. Naturally, for its inhabitants, it is their land, their home, and their local ways, with an inevitable sense of belonging and social construction of their imaginaries.

Recently, the Guggenheim Museum of New York organized the exhibition "Countryside, The Future," directed by OMA and Koolhaas (2020). Here, strictly non-urban spaces are reinstalled in the agenda of international architecture. This is associated with the countryside as an anthropocentric concept linked to food production, mining, energy creation, logistics, its support, the purchase of land for preservation, and other new services. It also includes some highly natural environments, some areas in the south of Chile among them. In this regard, the vast territory of the Patagonian coast also has potential. Certainly, interpreting Patagonia as a Global Garden, or as a non-residual countryside, also means admitting the challenges of a complex, open, and somewhat elusive governance. This applies at the national, provincial, and municipal state levels; at the level of other civil actors, both local and global; and at the level of economic corporate players of various ranges and power.

Insularities and Archipelagos

In the future, in the vastness of coastal Patagonia, as well as in other settings, it is recommended to operate in urban planning with insularities and archipelagos. Here it is advisable to inquire into insularities as creative and biopolitical innovation. Insularities may perch on vastness. They are specific, flexible within, and they may have various degrees of control. Their limits must be precise, whether they are or they are not clearly materialized. What is important is to mitigate and to compensate their environmental liabilities within the insular territoriality. Besides, these insularities may be conceived as manufactures of hybrid, natural/man-made landscapes (Sprechmann et al. 2008). Some authors speak about islandology and its diverse cultural reasons (Schell 2016).

In particular, a proposal of insularities in the private lands of El Doradillo in the coast of Nuevo gulf essays some conceptual and design hypotheses (Sprechmann and Capandeguy 2010). It is a border area off the Valdés peninsula system, which was declared a World Heritage Site. It was an environmental buffer assumed by the then provincial and municipal model of conservation. In the face of a regulation that tended to enable regular urban developments that would cover all large properties, a battery of compact packs was suggested in which tourist, co-residential, or environmental activities would concentrate, distant from the coast and under the plateau's edges (Fig. 2). These clusters interact**,** reducing intersecting, cumulative views. And a great part of the area of rural estates would be maintained as

Fig. 2 Proposal for compact packs in a protected landscape, El Doradillo, Valdés peninsula system, Patagonia. Idea of sustainable development limited to a battery of compact urban packs within large properties, with ecological restrictions outside the packs. Aerial view and types of packs. (Original design by Sprechmann and Capandeguy, redrawn by Roquero in 2010)

ecologically restricted areas, without the possibility of affecting the delicate natural patchwork. Each pack would have its specificity. This idea of urbanistic insularities, as quasi-autonomous and sustainable habitats, can be interpreted as a relational microcosm of the Global Gardens. Fuller (1969) was an inspiration, from his geodesic capsules with controlled atmospheres to his sentence Space-Ship Earth. In this regard, Fuller observed early that human praxis transformed the Space-Ship Earth into a large interior space, with its environmental limits. This approach anticipates later reflections on the Anthropocene, some already mentioned.

In particular, urbanistic insularities could act as settings of specificity, even mixture, in a planetary setting that is increasingly generic and homogeneous. It may be an alternative to possible continuous expansion processes inherent to littoralization of the coast. Could this not apply also to some future developments in the ocean or in Antarctica itself? All of which opens up a notable field of inquiry which transcends urbanism and ecology. That will involve other imaginaries and governances in a post-humanist time. As claimed by Sloterdijk (2006): "Island air makes you free."

Sustainability Crisis, Ecological Urbanism, and Adaptations to Climate Change

For the last few decades, sustainability has become a recurrent, challenging category. Sustainability would be a general phenomenon to do with the acquisition of awareness of the finitude of the world: "… when speaking about sustainability, a sustainability crisis is mentioned and also that –with different optimisms or pessimisms- the future compromises the very existence of the planet. /And it moves us to/… think how in the future –which is a near future- there would be situations that would enable to set in motion other ways of projecting, of planning, understanding by planning the production of plans and management capabilities" (Fernández 2017).

It is a necessary change in the positioning of architecture and urbanism, striving to understand the ecological behavior of the territory. Multiple authors problematize the notion of ecological urbanism (Mostafavi and Doherty 2010). They stress how the practices of so-called sustainable design filter into diverse trajectories of urbanism and architecture. One such issue refers to its articulation with consolidated disciplinary traditions. A second issue would be the empirical verification of certain backwardness in the categories of sustainable design applied to the scale of urban territory and greater territory. Hence, the vindication of an ecological urbanism transcends the rhetoric of sustainability. One paradox is that urban agglomerations are large consumers of space and energy and generate various environmental liabilities. Concerning buildings, it seems key to move toward buildings with lower energy consumption and other materials and building technologies.

An emerging category in the last few years is that of territorial resilience. This refers to the readiness, resistance, and continuous adaptation of the territories before external changes or shock situations (Sánchez-Zamora 2016). Thom (1987) identifies structural stability that involves recognizing territorialities within complex systems, which may change from one equilibrium scenario to another. The Patagonian coast seems to have a great territorial resilience. But its cities and towns are less resilient. Particularly, coastal flooding is acknowledged as a risk factor because of the alteration of beach lines and their natural protections (Kokot et al. 2004), also inland floods owing to an increase in occasional torrential rains (Kaless et al. 2019), and on account of tampering with natural urban drainage, coastal negative feedback in cliffs, or, in some cases, industrial and sewage runoff. It is also worth noting problems in the supply of freshwater for human consumption due to various causes, such as the decrease in flows from current sources, deficits in the conduction, and purification infrastructures, which will require deepening water studies in future scenarios.

Changes in the beach line, negative coastal feedback, and the shrinkage of beaches, with their significant tidal ranges, are relevant in cities and coastal towns in Patagonia. Various geomorphological studies have verified this phenomenon and open up explanatory hypotheses about coastal morphogenesis (Isla et al. 2002; Isla and Bujalesky 2004; Isla and Cortizo 2014; Kokot et al. 2004; Isla and Isla, this volume). Consider that some seaside avenues were built within the active coastal zone, the water coming to its edges with a certain annual recurrence, which increases backwearing erosion. This occurred in El Cóndor or, to a lesser extent, in Playas Doradas, both locations in the province of Río Negro. Moreover, port facilities like docks, sand extraction, and the frequent destruction of the first row of protecting or buffer dunes have altered the coast's dynamics anthropically.

In the future, due to the effects of global warming and on account of an increase of man-made urban littoralization, greater disturbances to city fronts, even to the first row of buildings, are to be expected. Consequently, new relocalizations will be necessary, together with flood mitigation works, not only regulatory improvements to minimize future impact. A whole field of public policy opens up, of base studies and prospective modeling. That will enable greater effectiveness to anticipate and mitigate *ex post.* Certainly, the morphogenesis of urban coastal fronts constitutes one of the most complex issues for urbanism in Atlantic Patagonia. In addition, possible new urban developments should be built farther from the coastline in worst case scenarios.

Another course of action would be to apply backup strategies for infrastructure and basic services. Water supply for human consumption would be a case in point. Foreseeing duplicate supply resources, even from a different origin, would be very sensible. One last field of action to be mentioned associated with ecological urbanism is the creation of centers for the consolidation, gathering, recycling, and disposal of solid waste. It is a critical issue owing to its dispersal effects on the vastness of Patagonia. How to reduce its generation? How to store, compact, recycle, and monetize? Another specific topic is the reuse of materials and infrastructure. To be sure, there will emerge practices and sensitivities from collectives like rotor, with its architectures in reverse (Devlieger 2017), and other innovative associative initiatives.

Clean Energy Infrastructures Conceived as a Manufactured Landscape and Objects of Desire

Since the beginning of the century, urban planning has been conceptualized in relation to infrastructures (Allen 1999; Sprechmann et al. 2015). These are the material and operational supports of the territories. These have their sectoral and performative logics, along with a proper territorial organization, material component, value as fixed capital, and social, ecological, and coastal landscape externalities. The infrastructures are not only utilitarian. These could also be conceived as objects of human desire and empathy with other species and with inert matter. Part of the architecture is distancing itself from visions centered on the design object enclosed in itself. Likewise, the disciplines of engineering are being articulated with the new conceptions of the territory.

Partly associated with ecological urban planning, it is worth looking at the notion of infrastructural urbanism. In this approach "… form matters, but it matters more for what it might do than for its appearance… Infrastructures are flexible and anticipatory… they accommodate to local contingency, simultaneously maintaining a general continuity… organize and direct complex flow, movement and exchange systems, and they function as artificial ecologies…" (Allen 1999). At present, a greater rapprochement between the infrastructure project and the architecture project is recognized. In particular, the notion of "… architectures as infrastructures, and infrastructures as architecture, wants to signify the need for project explorations that seek their reciprocal interaction… The key is in the interpretation of places, their geographical and environmental memory, as opposed to the idea of the tabula rasa, where everything is invented from zero" (Cohen 2019).

The Atlantic Patagonia, like other regions of South America, has infrastructure deficits, with absence of infrastructure projects (Cohen and Nanzer 2012). There are projects started, even budgeted, not finished and with somewhat opaque trajectories. Furthermore, very specific local problems are recognized. One of them is that of the blueprint of gravel roads, occasionally in inappropriate places, like the active zone of the coastline or on receding cliffs. Both are current situations on the shoreside road (Camino de la Costa) in Río Negro province. This was a notable work originally conceived as a scenic route to promote tourism, without a previous study of future externalities. Gravel roads, however, and their impact on humans and other species are an open question in the Patagonian habitat. Within this infrastructural view there is the clean energy infrastructure urban planning. These are renewable energies, which may (or may not) be of low environmental impact. That depends on the localization, format, and mitigation of the infrastructure. Large hydroelectric dams, like the ones planned on the Santa Cruz river, are examples of the difficulty of harmonizing development strategies and ecology. Energyscapes have urbanistic and territorial development potential (Ivancic 2010). Their conception should not only be sectorial but transdisciplinary, since this is a complex manufactured landscape.

The most delicate clean energy infrastructures are those located in ecotones, in intertidal zones and ecological corridors. Atlantic Patagonia is a case in point. Urbanizations and road and energy network infrastructures (power transmission lines, gas and oil pipelines), which get connected in order to reduce costs, may be juxtaposed here with bird fauna corridors and diverse significant coastal-marine ecosystems. Environmental risks and assumptions of such infrastructure change in the face of adaptation to climate change. This suggests deeply looking into the best micro- and macro-localization and solutions, possible decentralization, the reduction of negative environmental impact, and an analysis of such undertakings in terms of an ecological economy. It is also worth anticipating possible solutions after their decommissioning, regardless of the difficulty of their anticipation. An open point is the future of wind turbine structures after their useful life as such. Would it not be possible to explore the application of notions like Gunter Pauli's blue economy (2017) rather the more extended notion of green economy?

It is worth highlighting one line of research on the production of tidal and wave power in Atlantic Patagonia conducted from the perspective of urban planning and landscape design, from the team of Romagnoli-Pont-Serafini (Romagnoli et al. 2017). The triggering project was a tidal power plant off Punta Loyola in the estuary of the Gallegos river. This plant consists of a lake, a breakwater, a tidal power plant, and other equipment. These are articulated as a power and landscape infrastructure that boosts the extraordinary range between tides. Its authors set out to "… incorporate a multiplicity of scales, understand the natural biophysical processes, relegate the place of Man and place him within the ecosystem, change the concept of occupation for that of symbiosis, find in Nature and its components the order of architecture, redefine standardization: the singularity of infrastructure as a closed system designed exclusively in efficiency and economy" (Romagnoli et al. 2017). Later, the Romagnoli team has continued to work on coastal planning, proposing a Marine Energy Route. In this point, they are adding other explorations of tidal power in Puerto Santa Cruz and Puerto San Julián. They also propose a wave energy infrastructure at 3.5 km east of Puerto Deseado city, basing its localization on the directionality of the Atlantic ocean waves and the geomorphological requirements of such infrastructure (Fig. 3). A semi-open bay is thus created, with the capacity to host productive and water sports programs due to the decrease in waves on the other side of the infrastructure. The proposal reorganizes and improves urban-coastal vehicular and pedestrian connectivity through a series of scenic landmarks (Fig. 4). This proposal is more than just an energy landscape, since it operates as a piece of land art to be enjoyed by visitors.

Fig. 3 Proposal for Puerto Deseado's Wave Energy Park, Patagonia. Panoramic view. Wave energy infrastructure that considers the geomorphology and directionality of waves. Creation of a semi-open and protected bay with productive and water sports programs. An urban-coastal vehicular and pedestrian connectivity links a series of scenic landmarks. (Image courtesy of Romagnoli-Pont-Serafini, designed in 2020)

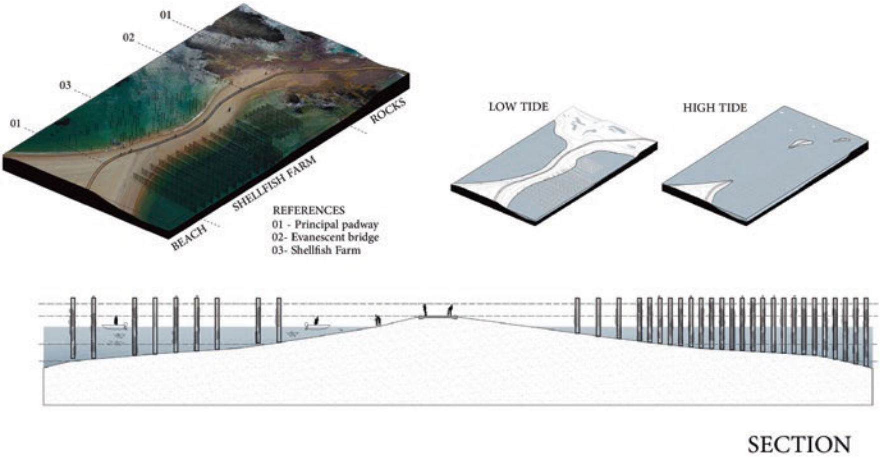


Fig. 4 Proposal for Puerto Deseado's Wave Energy Park, Patagonia. Conceptual diagrams. Graphic schemes on the operation of this Wave Energy Park at low and high tide. The proposal enhances the subjective and artistic perception of the vital evanescence of the tides. (Image courtesy of Romagnoli-Pont-Serafini, designed in 2020)

Inclusive Urban Planning

Recent urban planning tries to be more socially inclusive and equitable. On Patagonia's coast, urban planning of the citizens (urbanisms of the people) is to be recognized, which in some cases is vanishing. It is the temporary habitats of octopus fishermen by the intertidal zone, the sheds of other artisanal fishermen, the tents of temporary farm hands in estates in the lower valley of the Chubut river, or the irregular houses moving on the snow on tracks in Río Grande, Tierra del Fuego. Today, in several coastal cities there are some shanty towns (*villas miseria*, as they are commonly known in Argentina) and makeshift housing. They reflect the socio-territorial dualities of today's world and the haste to improve the living conditions of their dwellers.

Practices of a novel, self-managed, bottom-up urbanism may be imagined in the future of Patagonia. This urbanism could adopt diverse modes of initiatives and express imaginaries of different collectives and local and regional citizenships, the communities descending from native inhabitants among them. As already stated, the latter were persecuted, subjected, and almost decimated in the nineteenth and twentieth century in Patagonia. Their relegated vindications are focused on the Andes and steppe parts of the region.

In recent years, the category of urban planning with a gender perspective has emerged with force. In particular, the expression of a feminist urbanism would make its origin and its political dimension more visible. "*Feminist urbanism* provides a broad vision of people by affirming that women, men and non-binary subjects live and experience space in different ways, due to the influence of gender roles in the design and use of cities" (Col-lectiu Punt 6 2019). Feminist urbanism delves into narratives, problems, and modes that are alternative to the dominant urban approaches. Urban planning of the citizens and urban planning with a gender perspective nurture a substantive cultural change and collaborative work, with new sensitivities, focusing on attention, visibilities and challenges for action.

Urban planning with a gender perspective and urban planning of the citizens (urbanisms of the People) (Fundació Antoni Tápies 2007) will generate new living landscapes in contrast with valued landscapes: "… the idea of place, besides pointing to a geography, allows to refer to a social site which results from a spatial choice. The difference between living landscapes –whose meaning results from considering everyday practices in which the surroundings take on meaning– and valued landscapes –considered fixed by public policy-making- is situated in a tension in which permanence is disputed from two different spheres from which meaning may be built …" (Núñez 2016). In particular, this active positioning could be amplified in Argentine Patagonia, given the creative power of still little visible voices and the capacity of many local and regional society collectives.

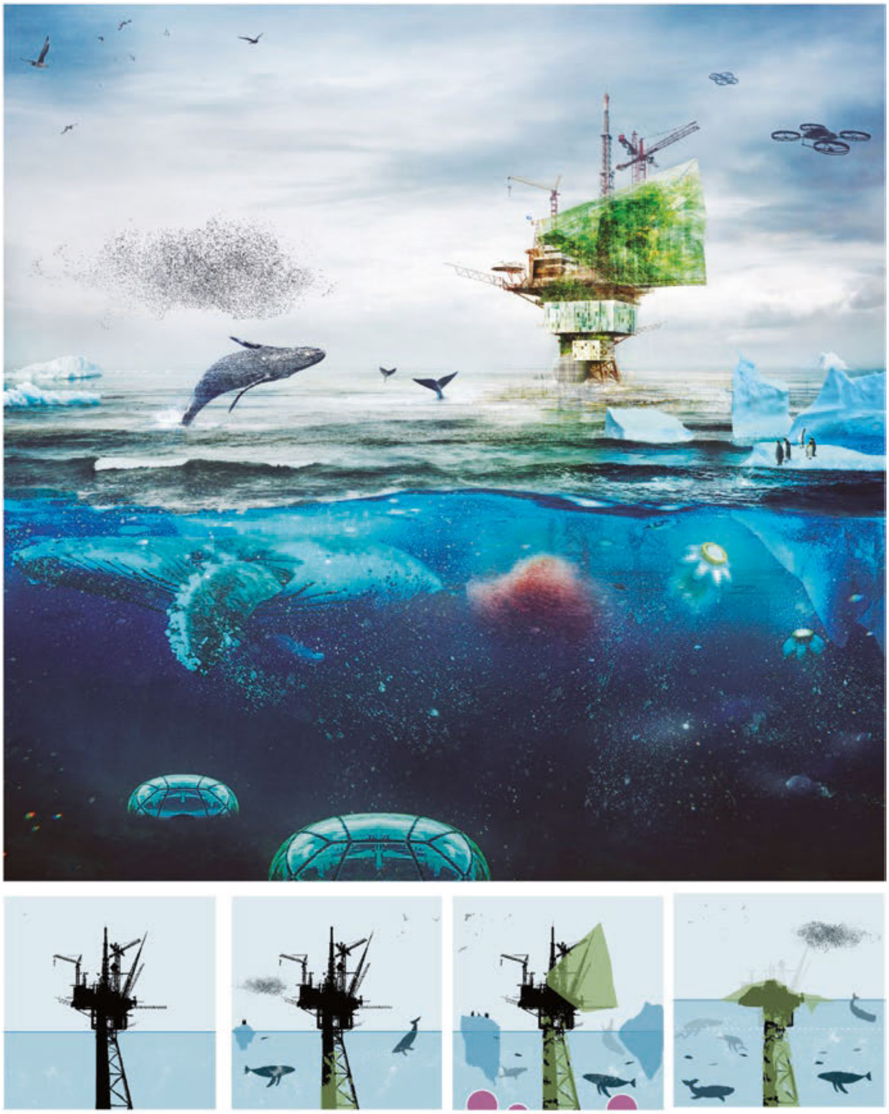
Multispecies Urbanisms

In a post-humanist vision, multispecies urbanisms could be conceived. Haraway (2019) stresses the need for a time of new assemblages of less separated species and of other biotic and abiotic forces: "right now, the Earth is filled with refugees, human and not, without refuge… Maybe, but only maybe, and only with intense commitment and collaborative work and play with other terrans, flourishing for rich multispecies assemblages that include people will be possible." The notion of an architecture and of multispecies urbanism transcends the notion of mixed programs of human, urban activities which thematize or facilitate productive, resting, or feeding processes of other animal or vegetable species or of provision of other ecosystem services. This is the case of some internationally emblematic projects by studios amid.cero9, R&Sie (n), Husos, and Scapes (Zaera Polo 2016).

Coasts, like Patagonian ones, with their land, sea, and intertidal components, with gulfs and coves, are very powerful territorialities to conceive this kind of symbiotic architectures, even strictly without direct human uses. In this text, a graphic sketch of a Symbiote Platform Project, in the South Atlantic, is presented (Fig. 5). It is a future reconversion of an oil rig in the vicinity of Tierra del Fuego or the Malvinas islands. This setting integrates an extended and substantive territoriality of the Patagonian coast, which transcends current political barriers. The proposal for this reconverted platform is a symbol of a new civilizing disposition. It is a biotic, multispecies, hybrid, metabolic, refuge, which profits from future abandoned infrastructures of the Anthropocene. The latter could also be dismantled and reassembled with different logics. This type of symbiotic actions could also be applied in underwater parks generated from wreck ships.

Epilog: A Cohabited Blue Patagonia

Patagonia in general, and Patagonian coast in particular, is a very vast territory, a complex *milieu*, with its geological, paleontological, and biological signs that refer to intrinsic macrohistory, social actors with their logics and imaginaries, and ecological and landscape phenomenology. Some issues, relations, proposals and practices in Atlantic Patagonia have been addressed in this chapter. The value of human capital is stressed in these southern latitudes of Argentina, with its sensitivity for ecology and its concern over present and future subsistence. This is inseparable from the wider environmental asset of this vastness. In parallel, various disciplines, urbanism among them, ecology itself, productive activities like fisheries, or power engineering, are at an embryonic renovation stage of theoretical, linguistic, and operational strategies. The above is mixed with the notorious changes in Information and Communications Technologies (ICTs), Big Data, and Artificial Intelligence (AI). Global warming, the crisis of human civilization, and post-humanism transform the very notions of territoriality, place, naturalness, and the human condition



ACT I
OIL RIG

ACT II
FIRST
MORPHOGENESIS

ACT III
SYMBIOTE
PLATFORM

ACT IV
ANOTHER
TIME

Fig. 5 Symbiote Platform Project, South Atlantic. Study image. Project exploration on a possible reconversion of an oil rig. The proposal activates the platform as a biotic, multispecies, hybrid, metabolic refuge, both technological and highly natural, within a future alternative ecological and *blue economy*. (Original design by Sprechmann and Capandeguy, redrawn by Sei Fong K in 2020) itself. All of this permeates and nurtures the views, practices, and disciplines of the territory, including urban planning as political action. Democracy and its public policies should also be rethought and focus more on the common good, including natural and cultural resources, a renewed vision of public services, and social information (Laval and Dardot 2015).

The point is how to move forward with urban planning practices in the midst of haste, adaptations, and significant paradigm shifts. In this regard, the tactical urbanism (Gadanho 2014) could be applied more. Urbanism is not alien to its excessive prescriptive tradition and its necessary articulations with democratic politics, with social groups and with life itself. Likewise, architecture and therefore urbanism as well are increasingly intertwined not only with the hard sciences but also with art and philosophy. In this regard, Moscato (2017) points out that: "… cities are only sustained by illusion. Crises are overcome by generating illusions… The best thing about architecture is the hope of transforming the world." Torres Nadal (2019), relying on Artaud, observes: "… it is those fictionalized realities that have compelled to construct unexpected, astonishing accounts and to be able to heed them, and to be able to find ourselves in them… Everything seems to tend towards the creative dissolution of architecture; not towards other forms of it, but towards other co-existences and other co-operations experienced on shared planes. 'Make kin, not objects'."

That is why this essay dealt with various associated approaches: the conceptualization of Patagonia as a Global Garden, urbanistic action by means of insularities, the increasing estimation of its non-urban settings (and not only its protected settings), the crisis of sustainability, and the possibilities of an ecological urbanism associated with new conceptions of territorial infrastructures. Additionally, two substantive trajectories have been proposed: delving into urban planning of the citizens and urbanisms with gender perspectives in this field and the possible development of a more inclusive multispecies urbanism. The previous keys are insufficient to approach positively toward the end of the Anthropocene, enunciated in the title of this chapter. For this, technical disciplines, such as life and Earth sciences, social sciences, urban planning, and even art, will surely be profoundly renewed. This will suppose philosophical refoundations of each discipline, new associations, cooperations and dilutions, and the emergence of other epistemologies. Architecture and urbanism cannot become dissociated from such renovations and dreams. That will allow to imagine and materialize a Cohabited Patagonian Coast, a "Cohabited Blue Patagonia", in a non-anthropocentric sense.

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Conservation of Coastal Atlantic Environments in Northern Patagonia: A Critical Review

Juan Emilio Sala

Introduction

The present work aims to analyze and synthesize, based on theoretical and reflective tools from philosophy, history, and political ecology, the multiple relevant dimensions of conservation science displayed in the coastal Atlantic systems of northern Patagonia in the context of global change. I start with a critical review of its changing and systemic logics, theoretical frameworks and concepts that shaped them, and the role of the actors and institutions that practice conservation in the territory. With this chapter, I will seek to make a proposal that will overcome the main contradictions and obstacles that the conservation of the coastal environments of Patagonia has been going through for more than 50 years, with particular emphasis on the Valdés peninsula (PV) region and the coastal northeast of the Chubut province Argentina. Thus, I will discuss – and review – ideas and not people or institutions.

The structure of the chapter will be as follows: it begins with (1) an analysis of the philosophical roots of conservation science; it continues with (2) the description of the historical processes followed by the conservation of coastal Atlantic environments in northern Patagonia and how they were strongly influenced by the above; (3) then, the multiple dimensions of the social-ecological systems (SES) perspective are presented, trying to demonstrate the overcoming implications of their implementation for the conservation of the coastal systems of Patagonia in the context of

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global change; and, finally, (4) a synthesis and future research that need to be carried out in this important region of the planet are presented.

Theories and Knowledge of Conservation Science

The canonical definition of conservation presented in the World Conservation Strategy, established by the International Union for Conservation of Nature (IUCN), the World Wildlife Fund (WWF), and the United Nations Environment Programme (UNEP), says that it is the "…maintenance of essential ecological processes and life-support systems; preservation of genetic diversity; and sustainable utilization of species and ecosystems…" (Talbot 1980). In turn, Conservation Biology (CB) emerged as a synthetic discipline (see below and Fig. 1a) academically organized in the USA in the 1980s (Soulé 1985; see below), although much of its theoretical framework was originally developed in Australia in previous decades (see Sarkar 2005).

Significant differences in approaches between the two traditions (i.e., North American and Australian) were resolved in the late 1990s by formulating a conceptual consensus framework for the design of protected areas (PAs) and/or reserves networks (Sarkar 2005). The problem of the design of the PAs/reserves networks became the first major theoretical problem that CB had to face (ibid.). In the USA, in the 1970s, conservation ecologists tried to solve it by applying the Theory of Island Biogeography (i.e., mathematical model based on the notion of equilibrium;

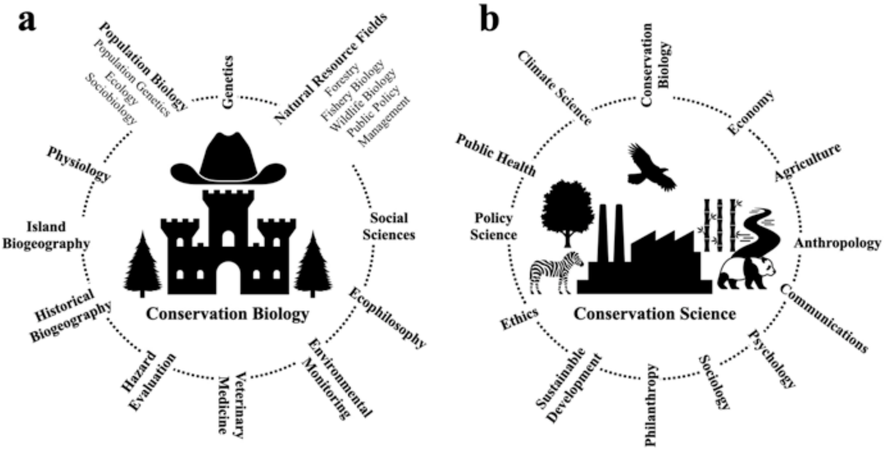

Fig. 1 (**a**) Representation of *synthesis* and *multidisciplinary* scheme of the "Conservation Biology" (CB) according to Soulé (1985), indicating the main disciplines or areas of knowledge involved; (**b**) representation of the "Conservation Science" according to Kareiva and Marvier (2012) in which the multiple dimensions of CB are part of a broader and *interdisciplinary* effort to protect nature. Adapted from Kareiva and Marvier (2012)

e.g., MacArthur and Wilson 1963). From this, a great controversy was generated, regarding whether few large or many small reserves should be designed (i.e., SLOSS – single large or several small). Its outcome was that the problem had no solution (Sarkar 2005). By 1985, when CB was born, it was clear that the answer depended on local and highly contingent factors (Soulé and Simberloff 1986).

Historically, the natural sciences (especially ecology) have been the only primary source of information and knowledge used to guide conservation action (see Bennett et al. 2017; Büscher and Fletcher 2020). However, many influential conservation scientists have long recognized the importance of integrating social and human considerations for conservation. The ecologist Aldo Leopold argued for the first time in 1935 that the fusion of those who study human, plant, and animal communities "…will perhaps constitute the most outstanding advance of the present century…" (Leopold 1966) – a task that was never fully accomplished during the last century.

Later in the twentieth century, Michael Soulé's influential article (1985) in bioscience placed the social sciences within the new synthetic discipline which he called conservation biology (Fig. 1a). Years later, gradually, a broader understanding called conservation science begins to emerge (Fig. 1b), which more directly recognizes the role of a diverse set of natural, social, interdisciplinary, and applied scientific traditions (Kareiva and Marvier 2012).

Currently, the role of the social and human dimensions of conservation and environmental management in producing robust and effective conservation policies, actions, and results has been recognized (e.g., Bennett et al. 2017). Thus was born the approach of SES with the commitment to integrate social and ecological considerations in the conservation science (see Berkes and Folke 1998; Berkes et al. 2003; Ostrom 2009).

Dichotomous Nature: Structuralism vs. Functionalism, Reductionism vs. Holism, and Complex Systems in Conservation Science

An important distinction to be made in the context of this work is that corresponding to the dualism between structural and functional organization of ecosystems (see King 1993). As I will show, this distinction is not just an interesting philosophical debate (De Leo and Levin 1997), since this type of dualism has important practical implications regarding the two different approaches to conservation that I will explain in depth below (see Table 1 and Fig. 1).

Thus, the dualism according to which ecosystems are interpreted presents two positions that, although they should be complementary and being indissolubly associated, in canonical approaches to conservation tend to focus on one or the other, in a rather antagonistic way (Sarkar 2005). On the one hand, the reductionist position (see Box 1) emphasizes the structural aspects of natural systems and focuses on

Table 1 Main characteristics of the canonical types of World conservation. It should be noted that there is a myriad of grays in between and even some more radical positions toward the peripheries of these two poles of attraction (see Büscher and Fletcher 2020)

Mainstream conservation	New conservation	References
Focusing on biodiversity (*biocentric*)	Biodiversity overestimated. The human being (i.e., that of modern rationality) returns to the center (*anthropocentric*)	Kareiva and Marvier (2012); Soulé (1985; 2013)
Natural preservation	"Human" needs	Kareiva and Marvier (2012); Soulé (1985; 2013)
Conservative position: Protect the "wild" environment from development	Developmentalist position: Search for a "correct" way to reconcile development and conservation	Wuerthner et al. (2014) and Büscher, Fletcher (2020)
Focus on PAs and charismatic species (e.g., lists of threatened species such as the IUCN red list) as main conservation tools. Strong strategic relationship with ecotourism with a clear elitist tendency	–*Initially*: PAs are important, but as long as they are approached through the community-based conservation (CBC) perspective through, e.g., the "Integrated Conservation and Development Projects" (ICDPs) –*Currently*: Solutions based on the financialization of nature and markets (e.g., market-based instruments as it includes bioprospecting, payments for ecosystem services, and carbon credits, among others)	Sarkar (2005), Larsen and Brockington (2018), Büscher and Fletcher (2020)
The corporate world as an enemy	Associate with the corporate world	Kareiva and Marvier (2012), Soulé (1985, 2013, Büscher and Fletcher (2020)
Fragile nature	Resilient nature	Lasaz et al. (2012), Soulé (2013)
Deontological ethics	Utilitarian/consequentialist ethics	Norton (2003), Sarkar (2005), O'Neill et al. (2008)
Intrinsic valuation of nature	Instrumental valuation of nature	Norton (2003), Sarkar (2005), O'Neill et al. (2008), Büscher and Fletcher (2020)
Focused on the structural organization of ecosystems (all species are "equally" important)	Focused on the functional organization of ecosystems (there are "redundant" species)	King (1993), De Leo and Levin (1997), Bergandi and Blandin (1998)
"Reductionist" approach	"Holistic" approach	Bergandi and Blandin (1998), Sarkar (2005)

(continued)

Table 1 (continued)

Mainstream conservation	New conservation	References
Strong dualism between society and nature	Weak dualism between society and nature (both categories have to be integrated as subsystems and seen as governed by flows of matter and energy): Attempted monism	Kareiva and Marvier (2012), Soulé (2013)
Top-down-led processes	Bottom-up-led processes	Spangenberg (2011), Ortega-Uribe et al. (2014)
Conservation associated with conservative (Fordist) capitalism	Conservation associated with neoliberal capitalism (post-Fordist and financial markets)	Larsen and Brockington (2018), Büscher and Fletcher (2020)

individual species and the population dynamics of species within isolated ecosystems (see Soulé 1986). On the other hand, the holistic approach (see Box 1) focuses on functional aspects at the macro-level (e.g., energy flows, nutrient cycles, and productivity), tending to neglect historical and evolutionary factors and ignoring most of the details observed at smaller scales of functional organization, as well as of the spatial and temporal distribution of organisms (De Leo and Levin 1997). Of course, the structural and functional perspectives of biological systems are not mutually exclusive. They simply reflect broad currents of thought in which many concepts and branches of ecological theories currently used in biodiversity and ecosystem conservation flourished (ibid.).

In this sense, the mainstream conservation approach follows the positions who defend the preeminence of structural aspects of ecosystem organization (see below). This conservationism almost, paradoxically, creationist, proposes to save species due to their high aesthetic (and landscape) value, from a highly fixist (conservative), structuralist, and essentialist conception of nature (see Sala 2007). As can be seen, this has very strong derivations in reductionist models in terms of practices, establishing as their maximum conservation tools the creation of intangible PAs, national parks, and/or reserves, lists of threatened species (Red List, IUCN), and the development of a very particular type of small-scale ecological tourism or ecotourism (see Büscher and Fletcher 2020; Table 1; see below).

As a reaction to this very reductionist conservation scheme (Box 1), the ecosystem-based management approach (UNEP 2011) emerged over time, to partially address some of the problems derived from sectoral or species-specific perspectives (see Sala and Torchio 2019). This approach may briefly be summarized in a series of principles and stages focused on the interactions between subsystems to resolve conflicts of interest and introduces adaptive management as a novelty (see, e.g., Ojea 2015 for an excellent review on this). However, this approach, from its genesis, lacks a more solid onto-epistemological change related to the ways in which (socio) ecosystems, the co-production of knowledge, and co-management are conceived (Sala and Torchio 2019).

With the intention to overcome these issues, in the last two decades, a subgroup of conservation scientists has concentrated on studying socio-ecosystems through the SES perspective (see Sala and Torchio 2019 and their discussion on this topic). Thus, from conceptions that are certainly more holistic, it will allow us the possibility of abandoning the reductionist roots of traditional environmental conservation (ibid.). This is why the debate around the axis of reductionism vs. holism fully enters into both conservation biology and the interdisciplinary science that is required to address environmental conservation (ibid. Box 1).

In relation to the study of ecosystems, as an example of complex systems, Burns states (1990, p. 193): "…The concept of ecosystem is powerful because it is holistic, emphasizing the interconnections among things and events sometimes distant in space and time…." But, at the heart of the ecosystem concept of the Odum brothers was the conceptual approach of Tansley (1935), who coined this term from the trophic-dynamic methodology of Lindeman (1942). This last author proposed an analytical-economistic procedure based on thermodynamics, by means of which he sought to measure the stocks and flows of matter and energy in the food webs of each ecosystem, as well as between the organisms involved in the web and their physicochemical environment (Lindeman 1942; see Bergandi and Blandin 1998). From a methodological point of view, this is nothing more than an analytical-additive-reductionist approach (Box 1), for which the whole is equal to the sum of its parts.

It is interesting to see how Eugene P. Odum (1971, p. 37), one of the fathers of ecosystem ecology, says that: "…In ecology, we are all fundamentally concerned with the manner in which energy is transformed within the system. Thus, the relationships between producer plants and consumer animals, between predator and prey, not to mention the numbers and kinds of organisms in a given environment, are all limited and controlled by the same basic laws which govern nonliving systems, such as electric motors or automobiles…," expressing a strongly reductionist metaphor (see Box 1).

Finally, epistemologically speaking, the preeminence of these ecosystem ecologists assign to the energy aspect of ecosystems reflects a tendency to accept physicalist explanations (i.e., derived from physics as a fundamental discipline) rather than holistic ones (see Box 1; Bergandi and Blandin 1998). Therefore, the ecosystem ecology, on which an important part of conservation practices rests, moves between two tendencies, which generally coexist in the same scientist (ibid.). In the next section we will see how all these issues are intertwined with the underlying debate: how and why to value nature.

Valuing Nature: The Underlying Debate

The two canonical positions of the world conservation movement of the last 20 years can be clearly identified in two seminal and dialectically related works: on the one hand the work of Soulé (1985) and on the other, and as a historical response to the first, that of Kareiva and Marvier (2012). This latest work has sparked what is known as the *Anthropocene conservation debate*[1]. The main characteristics between both approaches are summarized in Table 1 and in Fig. 1.

According to Kareiva and Marvier (2012), for CB (*sensu* Soulé 1985), as the basal theoretical influence of mainstream conservation – or fortress conservation (see Büscher and Fletcher 2020 and Fig. 1a) – biodiversity has only intrinsic value, regardless of its instrumental value (see Box 1). Protection of wild areas is the priority as highly anthropized systems have diminished their value for conservation. Human rights, equity, and the search for those responsible for the neglect of environmental conservation have received little attention. In contrast, these authors propose to (a) focus on the ecosystem services (see below), that ecosystems and biodiversity provides, as motivation for conservation; (b) seek conservation within the natural spaces where man works; (c) work with the corporate sector as a strategic partner; and (d) pay greater attention to human rights and equity (see Table 1). Thus, they argue that "…Conservation needs complementary strategies that simultaneously maximize the protection of nature and that of human well-being in the areas where people hunt, harvest, and live…" (Kareiva and Marvier 2012, p. 966).

This vision of the new conservation, so focused on the instrumental valuation of natural systems (Fig. 1b; Box 1), was quickly criticized by the defenders of the mainstream approach (Table 1). Thus, Caro et al. (2012) argue that the adoption of the Anthropocene as a structured category of conservation practice will dismantle conservationist and natural restoration objectives. If it is to believed that nothing should remain intact, e.g., invasion of species can be considered inevitable and unproblematic (ibid.). In the same sense, Büscher and Fletcher (2020) suggest that working with the industry introduces new risks, including damage to credibility through association with greenwashing schemes.

Soulé's response was swift. In Soulé (2013) he argues that the mission of this new approach is fundamentally humanitarian (in a pejorative sense): "…it must seek to encourage those natural systems that benefit as many people as possible, especially the poor…"; therefore, it should not be called conservation. This work sparked another round of heated exchanges and responses (e.g., Marvier 2013; Kareiva 2014; Wuerthner et al. 2014; Sandbrook et al. 2019; Büscher and Fletcher 2020).

It should be mentioned that in recent years, and as a dialectical reaction to the new conservation, a more radical version of the traditional or mainstream position of conservation has emerged, known as neoprotectionists (see Büscher and Fletcher 2020). This radicalization of the arguments of mainstream conservation leads, for example, to a return to the idea of intangible PAs, forcing the dichotomy between society and nature to the extreme and leading to one of its greatest exponents – and theoretical father of this conservation faction, Edward O. Wilson – to propose, in his relatively recent book, the preservation of 50% of the Earth's surface for nature (see

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[1] According to Büscher and Fletcher (2020, pp. 16–17), "…the *Anthropocene* thesis is essentially the assertion that human influence has come to dominate all nonhuman processes to the 'point that it can now be identified as a distinct layer in the geological record'."

Wilson 2016). As an outstanding issue, neoprotectionists, unlike mainstream conservation scientists, identify in late capitalism – or neoliberal – an important part of the causes of the biodiversity crisis that we are going through, calling into question such deeply rooted and associated dogmas to the idea of development, as those sustained by the economic growth and mass consumption (see Büscher and Fletcher 2020). For a matter of length, and because it escapes the objectives of the present work, I leave in the reading of Büscher and Fletcher (2020) the deepening on this new-old vision within the context of the Anthropocene conservation debate.

Finally, the conservation debate is more heated than ever, giving account of a revolution in process and an inexorable transformation (see Büscher and Fletcher 2020). The antagonistic positions presented in a brief way so far appear irreconcilable today (see Table 1), but this does not mean that alternatives are not being thought and worked on (e.g., Büscher and Fletcher 2020), as we will see below. However, although the conservation movement seems to be strongly divided (Soulé 2013), what a group of authors maintains, based on a global survey of the conservation community carried out on 9264 individuals from 149 countries, is that what we have is not a division – or rift – but a marked diversity, increasingly important, of visions and practices within the great global conservation movement (Sandbrook et al. 2019). Now we will see why all of the above is important to better understand the conservation science in the coastal environments of Patagonia and thus try to deduce the next inexorable dialectical movement – in historical terms – where the conservation movement is heading in this region of the planet.

A (Very) Brief History of Conservation Science of Coastal Atlantic Environments in Northern Patagonia

Toward the middle of the nineteenth century, the Euro-Argentine landowners of Atlantic Patagonia began a process of systematic hunting of birds and mammals, both marine and terrestrial, in clear tune with the process of accumulation by dispossession[2] (Harvey 2006, p. 153). This process, so characteristic of capitalism at this time, where the strengthening of international trade and the dawn of globalization – consumed during the twentieth century – began to press more strongly on the territories of the Global South, in search of primary products or of animal origin (e.g., guano, oil, leather, feathers, wool, etc.; see Conway 2005). In what it follows, I will show the role that hunting has had in terms of the very particular reaction that

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[2] Accumulation by dispossession is understood as an extension of the practices described by Marx in the origins of capitalism and includes the privatization of land, the expulsion of peasant populations, the conversion of the different forms of property into private property, the suppression of communal resources, the elimination of alternative forms of production and consumption, the colonial appropriation of natural resources, monetarization and taxation, human trafficking, and usury and borrowing through credit (Harvey 2006, p. 153).

was established among researchers and decision-makers in the coastal region of Atlantic Patagonia.

First Was the Hunting, Then Came Protection

Commercial whaling dates back to the mid-nineteenth century, becoming a powerful activity with more than 700 whaling boats hunting only off the Argentine coast (Conway 2005). In this period, the local sub-population of the southern right whale *Eubalaena australis* was driven almost to extinction (ibid.). Besides, the systematic hunting of sea lions – of two species, *Otaria flavescens* and *Arctocephalus australis* – as well as southern elephant seals *Mirounga leonina,* although to a lesser extent, was already practiced on the Patagonian coasts, where it was often carried out by the same whaling vessel crew (ibid., p. 56). This activity remained in force until well into the twentieth century. Records account for the slaughter of approximately 500,000 individuals of *O. flavescens* and an unknown number of *M. leonina* and *A. australis* (ibid.) (see Crespo, this volume).

In this sense, the case of PV is emblematic. Background from biology on pinnipeds in the PV and Punta Ninfas (southern end of the mouth of the Nuevo gulf, Chubut) has indicated that the populations of South American sea lion *O. flavescens* were highly affected by hunting: only between 1917 and 1953 more than 260,000 specimens were hunted (Gómez Ríos et al. 2012). Studies show that the number of individuals tends to grow, but is far from reaching the estimated figures for the period prior to systematic hunting (e.g., Romero et al. 2017). The population of southern elephant seals in PV – which was much less affected by hunting – is the only one of the pinniped species that has been steadily growing (Campagna 2002).

It should be noted that part of the *doxa* regarding the convenience – and justification – of the exploitation of sea lions was based on the assumption of the predation of fishing resources by this marine mammals (Bergadá Mugica 1955). First, the specific legislation was based on this line of argument, but subsequent evaluation studies showed that competition for the same resources between sea lions and the fishing fleet is minimal (Romero et al. 2011; Consejo Federal Pesquero 2016).

Another emblematic case is the attempted exploitation project that had the Magellanic penguin *Spheniscus magellanicus* as a target species and its subsequent reaction (see Conway 2005). Toward the end of the 1960s, in the pioneering province of Chubut, and as a reaction to the extractive activities of hunting different wild species described above, the institutionalization of ecological tourism began to occur (i.e., PAs and charismatic species as a tourist attraction). In 1964, the Provincial Tourism Law (No. 436) was approved in Chubut. This law created the Provincial Directorate of Tourism as an autarkic entity, marking a before and an after in the development of tourism in the Patagonian region of Argentina (Kuper 2009). For the first time a provincial state was going to be responsible and promoter of this activity. In this way, tourist activity appears closely linked, from its origin, with environmental preservation, as the most suitable means for the conservation of nature (i.e., mainstream conservation scheme; see Table 1).

Fifteen years later, on December 4, 1979, the PA of Punta Tombo was formally inaugurated, with the ultimate intention of protecting the largest Magellanic penguin colony in the world and developing scientific research there, mainly on this seabird species (see Conway 2005). Those most responsible for the establishment of this PA were the New York Zoological Society (i.e., later known as Wildlife Conservation Society or WCS; see below); an international conservation nongovernmental organization (NGO), based in the New York City Bronx Zoo Park (USA); and the Provincial Director of Tourism, Antonio Torrejón (ibid.).

Three years after the formal establishment of the PA in Punta Tombo, in 1982, a group of Japanese businessmen called themselves Hinode Penguin Argentina S.A. appeared in the province of Chubut, who, in association with local entrepreneurs, anticipated the initial slaughter of 48,000 penguins per year for leather production (centrally for the production of golf gloves) and the meat and fat would be processed for super-protein balanced feed (Tarak 1983; Conway 2005). Clearly, as a product of the epochal change that was taking place some years ago, the pressure of a part of the mobilized local civil society (see Tarak 1983; Conway 2005) and the transformation toward ecotourism, the productive project based in Magellanic penguins never saw the light of day (to read an excellent review of the case, see Tarak 1983), leading to the first great triumph of conservation based on tourism practice as an alternative development model (Kuper 2009; see Table 1).

Thus, the charisma of the Magellanic penguins responds to a social construction as a result of the change in the cognitive, economic, and political context of the 1970s and 1980s (Sosiuk 2017). It was the need to investigate it and manage the economic activities around it (mainly tourism and fishing) that began to establish the Magellanic penguin as a charismatic species of Argentine Patagonia (Sosiuk 2017). As we will see below, a similar journey has been experienced by the rest of the charismatic species of coastal Patagonia.

The Agenda of International Conservation NGOs

In 2004, a groundbreaking work was published through which many conservation science researchers opened their eyes, once and for all, to the real supra-structural interests of international conservation NGOs, today known as BINGOs (i.e., Big International Non-Governmental Organizations; see Larsen and Brockington 2018; Büscher and Fletcher 2020). Mac Chapin's controversial work (2004) entitled A Challenge to Conservationists was a true wake-up call. Mac Chapin recounted how in June 2003, representatives of the main foundations concerned with the planet's threatened biodiversity (e.g., Ford, Mac Arthur, Moriah, Wallace Global, CS Mott, and Oak) met in South Dakota for a meeting of the Advisory Group on Biodiversity. The three giants of global conservation – WWF, Conservation International (CI), and The Nature Conservancy (TNC) – had received many billions of dollars for their meager achievements and criticisms of processes of social exclusion in their conservation practices increased (see Chapin 2004).

Although WWF and TNC were born between the 1940s and 1960s (as was the IUCN), together with the general reordering of global institutions of the post-World War II period, it was only between the 1980s and 1990s that they expanded abruptly and at a global level (Chapin 2004). This growth begins with strong support from the United States Agency for International Development (USAID) and large foundations like Ford (ibid.). Today, TNC is the largest conservation organization in the world, with total assets that were $3 billion of US dollars in 2004 (ibid.) and reach almost $8 billion in 2020 (TNC 2020).

But, where does the money go? According to a financial assessment of the conservation sector, between the mid-1990s and the turn of the last century, the overall amount of funds available for conservation has decreased by almost 50% (see Chapin 2004). At the same time, the specific funds obtained by the BINGOs (mainly WWF, TNC, WCS, and CI) have increased in both relative and absolute terms (ibid.). And where does it come from? Since 1980, USAID finances BINGOs, as well as the World Bank and Corporations. In the case of WWF, 90% of project funding comes from these sources: "…So, somewhere along the line we stopped asking questions," said a senior official from that NGO (see Chapin 2004). Those corporations that most support BINGOs are Chevron, ExxonMobil, Shell International, Weyerhaeuser, Monsanto-Bayer, Dow Chemical, Alcoa, and Duke Energy, among others (ibid.).

In this way, USAID, the World Bank, and the Global Environment Facility (GEF) set themselves up as diplomatic agencies that work closely with – or against – national governments (see García Linera 2011; 2013; Boron 2013). Conservation BINGOs thus became agents of foreign policy, operating according to the interests of the centers of power and not necessarily in pursuit of environmental conservation[3] (e.g., Larsen and Brockington 2018; Büscher and Fletcher 2020).

As mentioned above, although the most important conservation BINGOs emerged in the post-World War II period, as part of the general reorganization of the world system, its capacity of penetration and incidence in the Global South, in general, and in Argentina, in particular, did not materialize until the consummation of the neoliberal experiment that emerged from Chile in 1973, but became globalized only after the fall of the Berlin Wall in 1989 (i.e., what the Italian philosopher Diego Fusaro calls the turbocapitalism; see Fusaro 2019). The 1990s in Argentina were more than fertile land for the flourishing of NGOs of all kinds, and those dedicated to preserving the environment were no exception. The Argentine Patagonia did not escape these logics. Thus, the international conservation NGO with the longest tradition in this region of the country is undoubtedly WCS. At the local level, this BINGO found a strategic partnership with the Fundación Patagonia Natural, with whom it executed a very important international financing line (i.e., a coastal conservation GEF project), among other collaborations.

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[3] To deepen the interventionist role of USAID and conservation BINGOs in Latin America, I recommend to see Garcia Linera (2011; 2013) and Boron (2013).

Conservation practices on the north Atlantic Patagonian coast were structured, dialectically, as a reaction to the hunting – real or potential – of, e.g., southern right whales, Magellanic penguins, South American sea lions, and southern elephant seals, among other species; which ultimately became charismatic (see Sosiuk 2017). In this process, the role of WCS was central, especially thanks to the work of Dr. William "Bill" G. Conway, a faithful exponent of mainstream conservation (Table 1). He was the one who established the WCS conservation strategy for Argentine Patagonia, concentrating particularly on the coast and sea, although not only (see, e.g., Gelin et al. 2017).

Thus, thinking about the coast, he looked for scientists who could take charge of the research that would support the conservation of these four emblematic species of Patagonia mentioned above and that later would become important tourist resources for the region (Kuper 2009). In 1970, Roger Payne began to work with southern right whales from "Campamento 39," an establishment belonging to the Argentine Navy but managed by WCS, located on the coastal margins of the San José gulf, PV. In 1982, Dee Boersma arrived to work with Magellanic penguins in the PA of Punta Tombo. Finally, Claudio Campagna began that same year to work with South American sea lions and southern elephant seals (Conway 2005, p. 165). All three quickly became indisputable referents of conservation in the region, influencing to a greater or lesser extent the public policies aimed to planning the management of natural resources of the great coastal-marine ecosystem of Argentine Patagonia (ibid.).

All these researchers had something in common: they belonged to the WCS and were strongly influenced by the vision of this BINGO. Besides, research agendas were determined by the funding of WCS (see Sosiuk 2017). According to this view of mainstream conservation, species –and the spaces they inhabit – have intrinsic value and they must be conserved for that simple reason, since it is the right thing to do: deontological ethics (see Table 1). In addition, species must be preserved because they are beautiful and give us their splendor. This is conservation of a clear essentialist, reductionist, biocentric, and conservative vision (see Sala 2007 and Table 1). Standing in a structuralist scheme to interpret ecosystems, they understand that all species are equally important, denying a priori the possible functional redundancies (see above; Table 1). However, and as we have seen before, the articulation with the tourism sector, clearly instrumental in the axiological terms and developed from a utilitarian/consequentialist ethic, was interwoven from the beginning, although each sector started from a different ethic and from an antagonistic valuation of species and their environments (see below). This is a contradictory process typical of the genesis of mainstream conservation (see Büscher and Fletcher 2020), which is expressed very strongly along the coast of Argentine Patagonia.

The conservation agenda structured from this BINGO, and developed – at least – in the coastal region of North Atlantic Patagonia, may account for its participation in certain achievements, such as the recovery of populations of marine mammals once commercially exploited (see above); the preservation of species of seabirds such as penguins, petrels, and cormorants; and the creation of coastal and marine PAs. But, it is equally true that it has blocked the plural, diverse, and inclusive productive development of the Patagonian coast and the articulation of conservation with local actors (e.g., artisanal fishermen; see, e.g., Marin 2017, 2018). This has fostered a type of elitist ecotourism, hardly accessible to the common people of the territories where such conservation is practiced (ibid.).

Contradictions of Conservation and Management in Coastal Atlantic Patagonia: Intrinsic vs. Instrumental Values

Public policies on conservation and management related to the Argentine Patagonian coast, in general, as well as those focused on PV in particular, whether they are laws, decrees, ordinances, or management plans, have been designed at the local, provincial, and national levels, but with an important influence from the international conservation agenda described above (see Marin 2017, 2018). In principle, the conservation of wild species and their habitats is sought in combination with an ideology linked to the notion of sustainable development. In this sense, the so-called participatory processes that have been experienced, in a very minority, in the last 20 years in the region, are implemented to involve the people who live and work in the PV. Such processes do not constitute a local peculiarity (see, e.g., the emblematic and successful case of artisanal fisheries of San Matías gulf; González et al. 2010), but are interesting local manifestations of the global attention toward participation, which characterizes – at least from the discursive – the current development and conservation agendas around the world (Kareiva and Marvier 2012; cf. Marin 2017, 2018; Sala and Torchio 2019).

Despite the context of global change impacting marine and coastal systems worldwide (see, e.g., Cury et al. 2008; Temmerman et al. 2013; Helbling et al. (eds), this volume), some successful local results, linked both to the management of tourism, fisheries, and in relation to the conservation of seabirds and marine mammals, there are still important challenges for government authorities and other local non-governmental actors that are part of the administration of the PA of PV (Stefanski and Villasante 2015). Beyond federal laws and local efforts to implement responsible tourism practices, certain threats still persist to the long-term conservation of both seabirds and marine mammals (i.e., the most important regional tourism resources), in particular, and Patagonian coastal-marine ecosystem, in general. For example, recent research shows that fishing activities, tourism operations, and pollution threaten Magellanic penguins and other seabirds, dusky dolphins *Lagenorhynchus obscurus*, and southern right whales throughout coastal Patagonia (e.g., Coscarella et al. 2003; Dans et al. 2003; Gandini et al. 2011; Sala 2013; Stefanski and Villasante 2015; Chalcobsky et al. 2017).

In the case of PV, the participatory processes and, in particular, the participation of people dedicated to artisanal fishing in the formulation of public environmental policies are more than unique and interesting (Marin 2017, 2018; but see González et al. 2010). Since the 1970s, a close relationship has developed between them, the scientific researchers and the decision-making spaces in the region (i.e., trialogue of knowledge, *sensu* José María "Lobo" Orensanz; see Marin 2017, 2018). Not by chance, this has been reflected in seminal works, at a global level, on common property regimes, such as those of Fikret Berkes (1989) and Elinor Ostrom (1990), toward the end of the last century.

This collaboration has focused more frequently on the management of mollusks and fish that are the objective of the three local artisanal fishing activities, namely: 1) the collection of shellfish by diving, 2) manual harvesting of coastal shellfish, and 3) fishing with shore nets (Marin 2017, 2018). Thus, the artisanal fishing sectors and science and decision-makers have also been involved in the general management of the PA of PV (see Marin 2017, 2018). In this context, the concept of participation was applied especially during the drafting process of the PV Management Plan (i.e., 1998–1999) and during the three attempts to review it, from 2010 onward, which, however, have been unsuccessful and inconclusive (Marin 2017, 2018). This precedent of participation is certainly atypical for the country due to the close relationship of mutual trust that was forged between the artisanal fishing sector and researchers (but see González et al. 2010). Another aspect that is more than remarkable is the fact that the knowledge they co-produced has been – in the past – at the foundation of government decisions on how to manage the biocultural heritage of the PV (for an excellent discussion on this, see Marin 2017, 2018).

However, in the last decade, the collaboration between the artisanal fishing sector and scientific research was not fully recognized by local government authorities, who tended to put the scientific knowledge produced by mainstream conservation in the foreground as the only basis for measures and legislation on conservation and for the management and administration of PAs (see Marin 2017, 2018 and its references). This was mainly due to the close link between receptive tourism based on nature (sighting of charismatic species) and the conservation of PAs in the province (it is necessary to remember that in Chubut the PAs are administered by the tourism ministry and not by the respective of environment, like the vast majority of the districts of Argentina). Thus, after some efforts to carry out a type of community-based conservation (CBC), more related to the new conservation scheme (see Table 1), it has returned to the practices of mainstream conservation.

These tensions and contradictions are expressed very clearly at the valorative level (i.e., axiology) in the conservation approaches that coexist on the Patagonian coast. Thus, while the conservation structured by the WCS agenda requires pristine spaces and unbothered species, without people interfering in its enchanting aesthetic display (intrinsic and aesthetic valuation of nature; Table 1), ecotourism (and its approach more focused on conservation of anthropocentric vision), with which it has been associated since the 1970s, has the mission of generating greater income, more jobs, and improvements for both visitors and their workers (instrumental and pragmatic valuation of nature; Table 1). This original entanglement has generated certain types of cross sterilization such as the repeated unsuccessful attempts to carry out the revision of the PV Management Plan, little or no real implementation of the measures and/or recommendations contained on this, and the increasingly close extinction of the artisanal fishers of PV (see Marin 2017, 2018).

Then, neither the intrinsic valuation of nature nor the one that values it in instrumental terms can be fully expressed. In addition to the valorative problem, it is necessary to introduce, at least, the main axis of social conflict – or dispute – related to conservation in Argentine Patagonia and worldwide, that is, conflicting social relationships with nature: mainstream conservation tends to preserve wild nature for the distant use of a global elite (high-level scientists and rich tourists), and new conservation tends to reconcile conservation and development for the more intensive but still sustainable use of local people (conservation practitioners and local communities). For all this, an overcoming approach is necessary for the conservation of coastal Patagonia, as we will see below (cf. Sala and Torchio 2019).

A New Hermeneutic for the Stewardship of the Patagonian Coast: The SES Perspective

In the recent history of hermeneutics (see Box 1), one of its missions was to subordinate its epistemological concerns to ontological ones so that comprehension is not only a way of knowing but a way of being. Thus, according to Vigo (2002), the characterization of hermeneutics should not only occur as a theory of comprehension but also – and fundamentally – as a human praxis. Then, hermeneutics should be understood not only as a theory of comprehension (Box 1) but also in its links with the dimensions of its, e.g., ontology, epistemology, axiology, praxiology, methodology, and teleology (ibid.).

The Anthropocene conservation debate can also be read in a hermeneutical way. Brian Wynne (1998, 2014) points out that this type of debate not only occurs in the field of true propositions but also in hermeneutical fields, seeking to analyze and synthesize the relationships between the multiple dimensions listed above for each specific hermeneutic. In this way, everything contained in Table 1 of the present work can be reinterpreted with this notion of hermeneutics that I use here (Box 1), in order to later understand better the overcoming nature of the perspective that I will address in the following sections: the SES.

The SES as a Dialectical Overcoming of Conservation and Management Contradictions

The specialized scientific literature understands SES as complex and adaptive systems, in which human societies are part of nature (Berkes and Folke 1998; Folke et al. 2016; Reyers et al. 2018; Sala and Torchio 2019; Fig. 2). The social component refers to all human activities that include economy, technology, politics, and culture. The ecological component refers to the biosphere, i.e., to the part of the planet where life develops. Both dimensions are interrelated and interpenetrate and

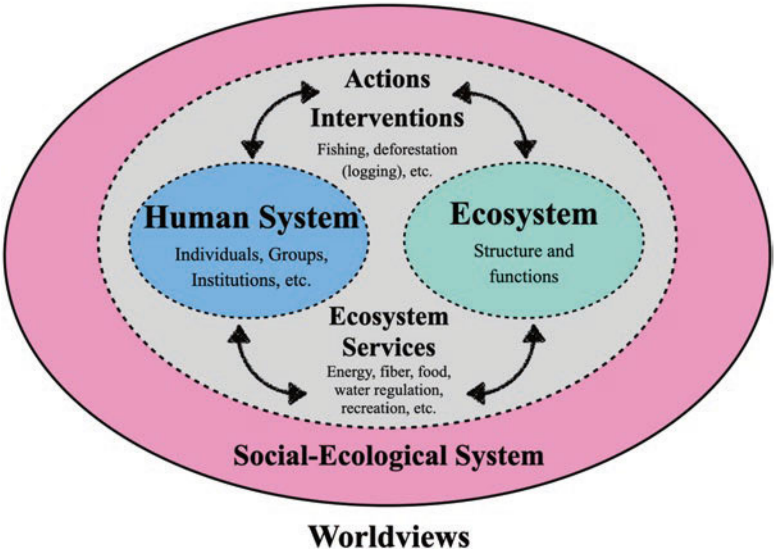

Fig. 2 Conceptual diagram of elements of a social-ecological system (SES). Human systems, comprised of individuals, groups, networks, and institutions (rules, regulations, and procedures), intervene to obtain goods and services from ecosystems. Actions and interventions include, e.g., the removal or planting of vegetation, harvest of animals, irrigation of landscapes, and construction of systems to control floods. These interventions directly and indirectly modify ecosystem structure and function. Adapted from Resilience Alliance (2007)

modify each other (see Sala and Torchio 2019). The SES boundaries are arbitrary and porous and depend on the question, hypothesis, or analysis perspective (Berkes and Folke 1998; Folke et al. 2016; Reyers et al. 2018; Fig. 2).

The old vision that considered the natural and the social worlds as separate (dichotomous dualism; see Table 1) should be considered definitively and dialectically overcome,[4] being replaced by a new hermeneutic that emphasizes that human societies, economies, and cultures are constitutive parts of the biosphere and transform it both locally and globally (Berkes and Folke 1998; Folke et al. 2016; Reyers et al. 2018). Simultaneously, and dialectically, people, economies, societies, and cultures depend on the biosphere since it gives them the material – and symbolic – substratum of their existence, and therefore both co-evolve[5] (Berkes and Folke 1998). From this interaction emerge the SES, whose components interact and condition in a dynamic and constant way (Fig. 2).

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[4] See in the Box 1 the meaning of dialectical "overcoming" used in this work.

[5] See the paradigmatic case of the Covid-19 pandemic analyzed in Sala (2020).

A central aspect of these interactions involves ecosystem services (ES), a contested concept which can be understood as the benefits that societies obtain from ecosystems and that constitute the basis of its development, prosperity, and sustainability (see Sala and Torchio 2019 and references therein; Fig. 2). They include supply, regulation, cultural or spiritual services that are supported by basic or life-support services, without which the aforementioned would be impossible (Reyers et al. 2018). As a synthesis to overcome the debate around the concept of ES, the notion of nature's contributions to people (NCP; i.e., these are all the contributions, both positive and negative, of living nature [diversity of organisms, ecosystems, and their associated ecological and evolutionary processes] to people's quality of life) was recently introduced in the specific literature of the sustainability and conservation sciences (see Díaz et al. 2018).

Then, the main challenge for conservation science in the times of global change, as well as for decision-makers, will be to depart from the vision of the environment as something separated from the social (i.e., an externality) and to value the biosphere as a precondition of social justice, economic development, and sustainability (e.g., Cury et al. 2008; Balvanera et al. 2020; Bennett et al. 2021; Helbling et al. (eds) this volume). In this sense, the hermeneutics of the SES allows understanding the complexity and adaptive management of systems in order to ensure the correct stewardship that guarantees the sustainability of life on the planet (Rockström et al. 2009; West et al. 2018).

Bringing all this to northern Patagonia and the analysis of its coastal-marine SES in the face of global change, it is necessary to emphasize that the agencies in the region in charge of decision-making in environmental issues are highly sectoral (e.g., tourism and protected areas, environment, science, and fishing), showing a weak articulation and coordination between them (see Alonso Roldán et al. 2015, 2019). In addition, although the different stakeholders in the territory recognize, partially and indirectly, their relationships with the coastal-marine SES, users and other local residents are more aware of the connections when they perceive the dangers of negative, real or potential, impacts (e.g., kelp gulls-whales conflict; see Stefanski and Villasante 2015), while some impacts are usually not so evident (see Alonso Roldán et al. 2019).

Then, as a new hermeneutic for the conservation and stewardship of the socio-ecosystems of the Patagonian coast, we will see that the perspective of the SES will allow us to overcome the criticisms developed by the new conservation to the hegemonic mainstream conservation vision in these territories (see above; Table 1). This will open the way to a new axiology that overcomes the false antinomy between intrinsic and instrumental values and will enable us to establish a new ontology that will overcome the artificial dichotomy among society and nature.

Transdiscipline as a Dialectical Overcoming of Criticism on Hegemonic Thought of International Conservation and Their Practices

> ...We then return to the imperative need to propose, live, learn and teach a complex thought, which re-weaves the disciplines as a possibility of humanity in completeness; and that only in this way would the eternal limitation and fragmentation of the subject separated from himself in the search for knowledge be overcome.... Nicolescu (2009).

As we have seen so far, the socio-environmental problems of coastal Argentine Patagonia are treated by dividing the system into fields of observation and action (natural and social) that ignore the possibility of understanding a total system of complex interactions. From governmental instances – as well as in the rest of the Latin American countries – an equally fragmented vision has led to the policies concerning the use of natural resources being elaborated and executed in a predominantly vertical or top-down way (see Table 1). Governmental action from this fragmentary approach responds poorly to local conditions, society's livelihoods, and community concerns, resulting in overexploitation, degradation, and irrational management of resources such as the complex problems as, e.g., the proliferation of the population of kelp gulls *Larus dominicanus* as a result of the energy subsidy derived, mainly, from fishing discards and open dumps and the subsequent attack behavior on southern right whales (see Stefanski and Villasante 2015).

In this context, the transdisciplinarity in the study and management of coastal-marine SES takes into account the situated, cross-sectoral, interrelated, and unpredictable nature of the current complex problems. Then, a methodological and epistemological change is necessary in the way in which socio-environmental problems are addressed in the Patagonian coast (see Sala and Torchio 2019).

Responding effectively to the dynamics of socio-ecosystems requires integrating environmental, social, and economic considerations of the various groups involved into decision-making (Spangenberg 2011; Balvanera et al. 2020). Communication and collaboration between different institutional levels, between sectors, and between social groups are therefore crucial elements. It is important to establish a widely accepted framework that allows institutionalizing the interaction between interest groups, negotiating opposing interests, and generating conflict resolution mechanisms, in order to determine the way in which decision-making and management of the biocultural heritage should be developed (Ortega-Uribe et al. 2014; Sala and Torchio 2019).

As we have seen, there was an attempt to oppose (antithesis) to the strongly sectoral, reductionist, and conservative vision of mainstream conservation displayed on the coastal Atlantic environments in northern Patagonia, from the participatory approaches developed in some specific cases (see, e.g., trialogue of knowledge in Marin (2017, 2018) and/or the ECOPES Project in González et al. [2010]). But, they did not manage to transform the praxiological (and much less the axiological) matrix of conservation, strongly influenced by BINGOs in the region (i.e., mainly WCS, but not only). The time has come to embrace the transdiscipline (see Box 1) in order to overcome the obstacles that conservation of Patagonian coast has been experiencing, still anchored in the mainstream versus new conservation axis.

The transdisciplinary co-design of projects, programs, and, in general terms, of possible solutions emerges as an advantageous approach, since it involves the stakeholders and the communities of a given socio-eco-system (e.g., artisanal fishermen from the San José and/or San Matías gulfs) as experts from their experiences, which ensures that the final product meets the needs of most of the actors, promoting a viable, situated, and effective process (see Sala and Torchio 2019).

Relational Turn as Dialectical Overcoming of the False Antinomy Between Intrinsic and Instrumental Values of Nature

It is now necessary to seek a new comprehension that overcomes the false antinomy between intrinsic and instrumental values of nature (Sala and Torchio 2019), which is generating so much damage to the environmental conservation throughout the world (see Klain et al. 2017; West et al. 2020) and that has a strong correlation in the Patagonian coastal region (see above). An alternative that is currently being developed with momentum (see Klain et al. 2017), to overcome this axiological dichotomy, is what is known as the relational turn (West et al. 2020).

From relational perspectives, centered on the philosophy of processes, the enduring objects that we generally perceive as substances or entities (e.g., bodies, bushes, penguins, whales, or rocks) are reconceived as temporal convergences, stabilizations, or events, within flows of dynamic relationships that already encompass what we tend to think of as human and natural aspects (West et al. 2020). This reverses today's hegemonic substantialist ideas, even in complex systems thinking: instead of processes and relationships being derived from entities, these are constitutive characteristics of entities (i.e., strong ontological recognition of processes and relationships; see West et al. 2020 and references therein). Consequently, concepts such as social and ecological are no longer understood as a reference to fundamental types of substances, but rather as tools that we use to make sense of our experience and act in the world (Wagenaar and Cook 2011). In summary, the most important thing to note is that the relational turn corresponds to a paradigm shift in conservation and/or sustainability sciences from assessing interactions between entities to an exploration and examination of continually unfolding processes and relations (see West et al. 2020 and references therein).

Thus, and with respect to the coastal Atlantic environments of northern Patagonia, a valuation experience of a clear relational nature – regardless of whether this was recognized or not – is that developed by the trialogue of knowledge coordinated by José María "Lobo" Orensanz from the decade 1970s, regarding to artisanal fishing in the San José gulf of PV, Chubut (see above). There, "Lobo" and his team dedicated themselves to valuing and preserving processes and relationships as fundamental tools to guarantee the stewardship of the biocultural heritage of this territory (see Marin 2017, 2018; West et al. 2018). To achieve this, he sought to consolidate healthy relationships (i.e., those that seek the reproduction of life and not the opposite) between the three most important sectors involved in this task: artisanal fishermen, scientists, and decision-makers. Through a permanent valuation and care of processes and relationships (construction of mutual trust and cooperation), and a strong respect for the own and contrasting hermeneutics of these three sectors, it was possible to establish effective co-management measures for this coastal socio-ecosystem of Patagonia (i.e., co-construction of transdisciplinary projects), with superlative success for all parties (see Marin 2017, 2018). As already mentioned, a similar process was experienced in the San Matías gulf during the ECOPES Project (see González et al. 2010).

However, as we saw above, the contradictions inherent to the logics of hegemonic conservation and the short-term views of local politicians prevented this successful model from continuing and spreading to other sectors, regions, and environments on the coast of the Argentine Patagonia (Marin 2017, 2018). The time has come to retake this type of relational approaches and thus overcome the false antinomy between intrinsic and instrumental values of nature (see Sala and Torchio 2019), to guarantee the proper stewardship of the coastal SES of Patagonia while promoting processes of social and environmental justice (see West et al. 2018), dialectically associated.

The Political-Relational Ontology as Dialectical Overcoming of Dichotomous Ontologies

> ...Politics arises in what lies between men and is established as relationships.... Arendt (2005, p. 95).

Throughout the chapter we have seen that the modern – and western – ontology that separates the human dimension from the environmental, natural, or ecological dimension largely explains appropriation by dispossession (Harvey 2006) and the irrational use of the biocultural heritage (Kothari et al. 2019). On this strong ontological distinction, mainstream conservation is based (see Table 1) and associated management measures are derived (see above), which have led to the profound – and sometimes paralyzing – contradictions that we have seen so far. Although the new conservation tries to give an answer to this, seeking to dissolve the dichotomy between society (culture) and nature, its strong link with the deepening of the commodification of nature, and the association with the financial and corporate world that has led us to this point (i.e., Anthropocene, global change; see above) make its implementation impossible by those who want to guarantee socio-environmental justice processes in the territories. For this later type of conservation, nature is at the service of man, and the laws of the market (objective, pure and universal) must be allowed to guide conservation processes (see Büscher and Fletcher 2020). This shows that in ontological terms, despite discursively holding the opposite, the new conservation remains anchored in a strongly dichotomous modern ontology (i.e., nature for the well-being of man).

A proposal that overcomes this dichotomy or ontological dualism, capable of accounting for the enormous ontological and valorative (axiological) plurality existing in the territories, in general, and in coastal Patagonia, in particular, is that of what is known as ontological turn (Holbraad and Pedersen 2017). The ontological turn brings together a set of plural perspectives that coincide in their interest in proposing alternatives to the dualism between nature and society/culture that structured modern naturalism (ibid.). By questioning the conception of what-is-real, these perspectives claim alternative ways of understanding the articulations between the natural and the cultural, and from there they pose interesting challenges for understanding the social relations of the contemporary world (ibid.).

The ontological turn represents an intellectual enterprise of particular magnitude: it aims to dissolve the certainties that modernity forged about nature by judging them reductionist (Box 1), ethno(Euro)centric, old-fashioned, and, to a certain extent, naive (Ruiz Serna and Del Cairo 2016). In the field of socio-environmental conflicts, certain lines of political ecology claim that conflicts of cultural distribution cannot be ignored (ibid.). In this sense, the ontological turn proposes conceptual keys that may be interesting to understand the configuration of such conflicts.

Besides, the ontological turn is compelled to embrace the multiplicity (plurality) of existing ontologies in the reality of the territories (Kothari et al. 2019), and this requires an important opening of thought for those who practice it, since, as we will see with a concrete example: what-is-there – and how to value it – is still an eminently political problem (Blaser 2013a, b, 2019). Here it is convenient to take up the example of the trialogue of knowledge experienced in the San José gulf coast of PV. From all the topics covered in this chapter, it is possible to understand that the three sectors that were part of the trialogue (i.e., fishermen, scientists, and decision-makers) express different and even contrasting hermeneutics (Wynne 1998, 2014; Box 1).

Then, on the ontological level, these three sectors understand very different things when they refer, for example, to a scallop (e.g., *Aequipecten tehuelchus*). This is known as ontological conflict (see Blaser 2019). If the relationship between these three sectors is based on a different understanding of what they have, suppose, in their hands, but they agree that they want to preserve it, the possibility of ontological negotiation can only occur by understanding those processes as political ontologies (Blaser 2013a, b, 2019). This implies the ethical-political decision not to impose an ontology on the others, as modern western science usually does, resolving the conflict from its reductionist program and the concomitant jibarization of the knowledge – and practices – that this type of hegemonic science produces (see above; Sala 2017).

It is even intuitive that if processes and relationships are valued and ontological status is conferred on them, the *agora* of ontological-political negotiation between hermeneutics can – and should – be the process of transdisciplinary co-construction of the co-management measures that are generated from the articulation of these three sectors. The resolution of the conflict about what-is-there is resolved from relational-political negotiation (Blaser 2019), as suggested by Hannah Arendt (2005) in the sentence at the beginning of this section. Of course, I am not naive and I foresee very serious conflictive issues around the differential dynamics of power between sectors, but these tensions can be treated and surpassed much better when the referents of each sector share the same physical space of interaction (Fabinyi et al. 2014). Even there, the post-positivist and/or post-normal scientific sector could play a central role in mediating between sectors (see Sala and Torchio 2019).

Synthesis and Future Research

In this chapter I have gone through the state-of-the-art debates, both conceptual and praxiological, around conservation science, evaluating its implications on the conservation of coastal Atlantic environments in northern Patagonia. I begin with the most used theories in environmental conservation, their philosophical roots, and their contrasting and dichotomous searches – and strategies (e.g., nature vs. society/culture; reductionism vs. holism; structuralism vs. functionalism; intrinsic vs. instrumental valuation of nature; mainstream conservation vs. new conservation; among others) – when it comes to knowing and understanding the (socio)ecosystems with which it must deal. Then I have analyzed how these contradictions are expressed in the Patagonian coast, generating a series of challenges for the conservation and management of the biocultural heritage of the region. Finally, I present the central arguments of what, in my opinion, is an overcoming approach to deal with these contradictions: the hermeneutics – in constant co-construction – of SES.

Thus, I saw that to overcome the criticisms of the single – and hegemonic – thought of mainstream conservation expressed by the new conservation, the SES perspective offered us transdiscipline as a tool for the co-construction of knowledge legitimized by the process, situated and applicable to each territory, and sustainable over time, thanks to the involvement of all stakeholders from the beginning. We also saw that to overcome the contradictions that exist in the conservation of coastal environments in Patagonia, emanating from the false antinomy between intrinsic and instrumental values (Sala and Torchio 2019), the incorporation of a relational turn is presented as an excellent alternative to explore (Klain et al. 2017; West et al. 2018, 2020). Finally, I seek to address the dialectical overcoming of the main modern dichotomy between nature and society/culture, proposing as an alternative the political – and relational – ontology, typical of the hermeneutics of SES (Blaser 2019). All these points, treated briefly and in an introductory way in previous sections of this chapter, require a deepening of research, both worldwide and, above all, in coastal Patagonia.

Finally, it is necessary to understand that to address, in material terms, the overcoming of the main contradictions and obstacles that the conservation of the coastal systems of Patagonia has been going through for more than 50 years by the application of the SES perspective, it will require a sustained, inter-, and transdisciplinary research effort. Then, and to better understand the dialectical processes linked to conservation in Patagonia, it will be necessary to investigate further the characteristics regarding the political (top-down vs. bottom-up) and economic visions (no development vs. conciliation of development and conservation).

To this aim, more research groups will be necessary addressing the socio-environmental conflicts of these territories from the tools of all sciences and the capacity for co-construction with other knowledge and hermeneutics (see Sala and Torchio 2019). These researchers must be armed with a lot of patience and commitment to socio-environmental justice (see, e.g., Bennett et al. 2021), because the search for solutions to socio-environmental conflicts in the context of global change cannot occur with scientists detached from the realities, needs, and agendas of the human beings that inhabit the coast of Patagonia, starting with the most vulnerable to reach everyone.

Box 1 Definition of the main philosophical concepts and terms used in this work. The concepts/terms are presented following the order in which they are mentioned in the text

Dialectic Is the conception that defends the *multilaterality of relationships* involved in any *real process*, as opposed to the schematic restriction of any process to a *single line* of relationships. Everything is interconnected and that there is a continuous process of change in this interrelation. The three characteristic movements of dialectics are the *thesis*, the *antithesis* (or contradiction to the thesis), and the *synthesis* or *overcoming* (in German "*Aufhebung*": abolition and conservation).

Epistemological reductionism Was the tool – or strategy – chosen by the members of the Vienna Circle, and the neopositivist science, developed, above all, from the 1930s, for the long-awaited *unification of knowledge*. According to this type of theoretical (or epistemological) reduction, it is possible to replace a theory A by another with greater explanatory power B. Then, and in this case, there will be an epistemological – or intertheoretical – reduction from A to B.

Ontological reductionism Can be understood as the link between the different domains of reality, according to which the entities of a given domain are, ultimately, entities of a more basic domain.

Methodological reductionism Is understood as those practices where the methodologies established for entities of a lower order are used with the aims to study, analyze, and explain entities of a higher level (e.g., genetics to explain behavioral ecology).

Holism Is the theory that parts of a whole are in intimate interconnection, such that they cannot exist independently of the whole, or cannot be understood without reference to the whole, which is thus regarded as greater than the sum of its parts.

Intrinsic value of nature Nature has value, independent of people.

Instrumental value of nature Being in/seeing nature brings people pleasure or satisfaction.

Relational value of nature Considers the appropriateness of how people relate with nature and with others, including the actions and habits conducive to a good life, both meaningful and satisfying. In philosophical terms, these are relational values, i.e., preferences, principles, and virtues associated with relationships, both interpersonal and as articulated by policies and social norms. Relational values are not present in things but derivative of relationships and responsibilities to them.

Hermeneutics Is understood as the art and theory of interpretation that aims to clarify the meaning of texts, starting from their objective bases (grammatical meanings of words and their historically conditioned variations) and subjective (authors' purposes). Wilhelm Dilthey turns hermeneutics into a specific method of the social sciences (see Dilthey 2010), called to ensure the "comprehension" of social events and starting from the subjective purposes of historical figures. "Comprehension" is opposed to "explanation" in natural sciences, which is linked to the process of abstraction and establishment of the general and the universal, such as natural laws.

Transdiscipline Emphasizes "going beyond" disciplines, transcending them. Transdiscipline concerns, then, an inquiry that at the same time is carried out between disciplines, crosses them through, and continues beyond them. The goal has changed; it is no longer limited to discipline, but attempts to understand the world under the imperatives of the *unity of knowledge*, but without using reduction as a unifying tool.

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Concluding Remarks: What Do We Know, and Where Do We Go from Here?

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Throughout this book, we showed how the different drivers of global change (GC), whether of climatic or of anthropic origin, shaped the environment, biodiversity, and human societies of Atlantic Patagonia. While the changes in climate have been rather mild so far, or perhaps remained hidden over time, the evidence indicates that the anthropogenic factors have been the main causal agents of deterioration of environmental quality and losses of biodiversity of the coastal marine ecosystem. Therefore, any strategy for adaptation to GC should focus on the recognition of the human dimension as a causal source of problems and on the search for solutions within that context. However, the large evidence of the effects of anthropic causes should not hide the importance of climatic stressors. The climate in Patagonia has been warmed up since 1950, and this trend will probably continue in the future. Extreme rain events are also expected to increase, and wind intensity is showing a clear negative trend for most of the coastal areas, confirming a pattern of change. In the ocean realm, the sea surface temperature (SST) shows a significant positive trend north of ~50°S and negative south of this latitude, and it is expected to continue in the future. Likewise, an increase in acidification of the ocean surface

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between −0.35 and − 0.40 is expected to occur over the next 70 years (Hoegh-Guldberg et al. 2014).

For the different faunal groups, the most important expected change in the Patagonian coastal ecosystem is a southward shift range of warm-temperate species or alterations in phenological traits due to changes in environmental drivers. This has been evidenced in vertebrates and may also occur in top predators, although with greater uncertainty due to cascade effects through the food webs. Also, the desiccation stress on Patagonian rocky shores is expected to get worse in the next decades; this, added to the consequences of acidification, calls for a thorough evaluation, especially in regard to their effects on marine invertebrates with calcareous skeletal structures in Patagonian coastal communities.

Bioinvasions have been also recognized as a huge driver of changes. Thus, to forecast future invasions, it is essential to gather long-term ecological survey data to be combined with bioclimatic modeling. Therefore, strong efforts should be put to create databases of functional traits potentially relevant to explain the distributional range changes in marine faunal species and to evaluate how these traits may act as indicators of future scenarios of functional organization of marine communities.

After focusing on the biodiversity of aquatic communities of the Patagonian Atlantic coast, we have also learned that much experimental work using multiple scenarios (e.g., pollutants, in combination with UVR, warming or ocean acidification) is needed, not only on organisms but also across the marine food webs. The interactive effects among variables seem to be especially relevant, as antagonisms, synergisms, as well as additive effects are the common naturally response. Also, the inclusion of the environmental variability expected due to extreme climate events for Patagonia is an urgent task.

As previously mentioned, anthropogenic stressors (i.e., market forces, overexploitation of fisheries, pollution) have dominated as drivers of changes in the history of Patagonia. The development of the Argentine fishing sector reflects the globalization that took place since World War II. This, in turn, gradually revealed a process of expansion of geographic, bathymetric, and taxonomic boundaries, as well as the consequences derived from inappropriate management systems that led to the overexploitation of many resources. The adoption of fisheries management systems based on property rights, and the incorporation of ecosystem considerations, appears as a promising alternative to overcome the failures associated with olympic fishing schemes and top-down management.

In addition to anthropogenic factors, increasing temperature and acidification appear also as a threat, mainly for small-scale fisheries targeting shellfish. Likewise, the southward expansion of the subtropical gyre and the Brazilian current, as well as the variation in wind patterns in the northern Patagonian shelf, could affect the seasonal northward extension of Magellanic resources associated with cold and salty waters. In addition, it has been speculated that the SST changes could also have a significant effect on the recruitment dynamics of the hake southern stock. The very important plausible effects of climate change on early stages of ecological key species (i.e., anchovy) and main fishing resources are practically unassessed, and this is a significant gap.

The problems derived from the interactions between nature and society/culture in Patagonia have been exposed in this book from two interesting perspectives: the urban development and the science of conservation of coastal environments. After recognizing that global warming and the crisis of human civilization transform the notions of territoriality, and the human condition itself, the need for a change of paradigm in the urban planning practices is proposed. Some emerging approaches and perspectives, such as the conceptualization of Patagonia as a Global Garden, or the development of a more inclusive multispecies urbanism, undoubtedly constitute true challenges for the Patagonian human minds. Under the perspective of conservation science, some contradictions arose from the false antinomy between intrinsic and instrumental values. In this sense, the socioecological system (SES) approach was proposed as an alternative (conceptual and operational) to address the overcoming of main contradictions and obstacles to the conservation of the coastal systems of Patagonia. However, this seems to be a hard task that will require a sustained, inter-, and transdisciplinary research effort and strong political commitment and broad stakeholder representation.

In summary, climate change is an uncertain threat to Patagonia marine ecosystems, its services, and their human populations. We need an urgent evaluation of the vulnerability of communities and ecosystems to future changes to have more realistic predictions to face GC.

A Novel Ecosystem: When the Change Began

It is evident that the processes of formation of coastal environmental structures have a relatively recent history: the sea as we see it today is a relatively new ecosystem, with only a few thousand years of evolutionary history. It is disturbing to think that what we see today as the immensity of the sea, a few thousand years ago there were only extensions of territory with features similar as those of the current coastal reliefs and steppes. During this time and through physical and chemical processes, natural forces drove what we consider today as environmental "patterns."

Thus, fluctuations and trends in environmental variables that have been registered in recent decades, or those that emerge from future predictive models, must be interpreted according to appropriate spatial and temporal scales. Any evidence of environmental change (climatic and anthropic) should be analyzed in the context of a dynamic ecosystem that 10,000 years ago (or even less) did not even exist as such. Thus, we are looking at an ecosystem whose species, populations, and communities, far from being immersed in a stable and predictable environment, are, on the contrary, subjected to different types of selective pressures, even of anthropic origin, in the context of a dynamic evolutionary scenario.

Humans have been present in the Patagonian coastal ecosystem for more than 6,000 years. We have long drawn on its resources and this remained almost unchanged for much of the time. However, the arrival of Europeans 500 years ago, with their culture and technologies, produced disruptive changes on this status quo. Thus, the process of colonization, with the introduction of the horse, livestock, and oil and gas production, until the appearance of fishing, was the first great anthropic driver on a global scale. Since the middle of the last century, with the beginning of the Anthropocene, and in parallel with the global increase in the World's population, the rate of consumption rose even more sharply. Consequently, the demand for natural resources, mainly food and energy, has been extended to the most distant parts of the world through the process often termed globalization. At the same time, the extraordinary emissions of greenhouse gases that took place since then have generated a series of indirect effects, such as an increase in temperature of the atmosphere and the sea, acidification, and other cascading effects that we do not perceive yet. Thus, the GC has begun to leave its marks even in the remote confines of Patagonia.

What This Book Leaves Us

In this book we reviewed the impact of GC on the three components of the overall system, i.e., environment, biodiversity, and ecosystem services, focusing in the recent 6,000-9,000 years. If any feature emerges from the content of this book is the complexity of the problem, since drivers of change not only produce different effects on the components of the coastal environment, but they also interact in complex manners. For example, the variations in both temperature and precipitation are ultimately involved in shifting the freshwater and sediment transport and hence in the transportation of toxins from terrigenous sources through coastal environments and then into food webs. As Valiela (2006) stated, human beings are conducting a global scale experiment in bottom-up and top-down control of coastal ecosystems.

Beyond the information gathered, this book ends up by posing two important challenges: first, the need to fill a large number of information gaps as a requisite to understand how the GC drivers will affect us and, second, the ineluctable need as a society to adapt to these changes. Until a few years ago, the adaptation to climate change was a topic that only an elite of academics and some planning experts from central governments spoke about. However, today it is an issue that has been installed in the society and the governments. This happened in part as a consequence of the media coverage of catastrophic events such as droughts, floods, or the great fires in Australia and the Amazonia, whose causes have been largely attributed to natural forces caused by climate change and anthropogenic pressure (agriculture expansion). In this context, more or less explicitly, governments have taken adaptation to climate change as part of their management agenda. Federal and local governments, at least in Argentina, have created political offices dealing with climate change in the spheres of environmental areas. Apparently, climate change has become a public policy issue, for which it will require an explicit strategy, given the general interest and the need for an informed society about its derived effects.

However, in spite of the negative effects repeatedly evidenced in reality, it is clear that both the concept and the operational framework of environmental governance will have to be reviewed and reinvented given that, until now, institutional management has been running from far behind the environmental problems. In Patagonia there is already an initiative since the mid-1990s – the Integrated Coastal Management (ICM) in which environmental problems, resource management, and conservation of biodiversity in the coastal zone are issues institutionally addressed. This initiative included the adoption of specific legal frameworks, the implementation of conservation management plans, the improvement of the marine protected areas management, and public participation as part of the strategy (Fundación Patagonia Natural 2010). However, and after more than two decades of efforts to advance toward a sustainable use of the environment and biodiversity in the coastal ecosystem of Patagonia, in most cases those experiences have been left immobilized under the state bureaucracy without even completing an evolutionary cycle of the ICM. Even more, in those years they did not even foresee addressing the problems derived from GC.

The dynamic nature of the GC effects on the different elements of the society-nature binomy determines the need to overcome the problems derived from inappropriate management schemes and appeal to innovative perspectives that explicitly recognize the interactions and feedback between the elements of the natural and socioeconomic subsystems. However, the challenges of implementing concrete actions for adaptation to GC are enormous and complex, because in part it is about fighting against a multifaceted and invisible enemy, whose negative effects will be seen occasionally and in a fragmented way. Hence, the task requires an approach whose definitions and scope exceed the aim of this book.

Future Directions

This book makes us realize not only about the importance of filling a large amount of information gaps about the effects of GC but also on the need – as society – for preventing and adapting to those changes. Both challenges have an important role reserved to science: regarding the former, through the observation/monitoring of environmental variables (including anthropogenic), experimentation, and modeling, as essential activities for the generation of knowledge and as for the second, through the assessments and syntheses (i.e., Steffen et al. 2020). While syntheses become essential to build new knowledge at a fundamental level, the assessment acts as a bridge between the scientific community and the society, facilitating new directions in research, following feedbacks from the social/policy sector. Hence, a new science, with interdisciplinary research methods, is needed for the Patagonian ecosystem in the context of GC.

From the information gaps identified in the different chapters of this book, we can conclude that our scientific community faces an enormous task in relation to building stable/systematic programs for the observation and monitoring of long-term environmental data. With few exceptions, the Argentine scientific system lacks long-term data series on environmental variables (mainly oceanographic), and studies on climatic variability at regional and local scales are much needed. Likewise, data series on biodiversity patterns and population parameters of marine species and communities are really very scarce, and in the case of variables and indicators of socioeconomic activities related to marine ecosystem services, they are practically missing. A first and great advance to overcome these deficiencies would be to make accessible to the scientific community all the historical databases collected by national organizations, within a short timeframe in order to be useful for science and the society.

Regarding experimentation and modeling, and although there are important capabilities at the level of some institutions, the development of these scientific lines can still be considered regionally in an incipient state. These deficiencies in the scientific system also prevent progress in the synthesis and the assessment task. Therefore, any strategy that is intended to be implemented to deal with GC problems must consider all of these components. Only with new and more integrative experimental approaches, including long time series that allow better definition of seasonal changes of diverse variables, we will be able to understand the potential impacts of GC at the ecosystem level and eventually provide solutions to mitigate it.

Finally, and beyond these basic ideas that we propose to guide the action of a “Patagonian Science of Global Change,” we believe that it is very important to advance in a change of perspective regarding the construction of public policies dealing with the GC. We believe that it is really necessary to explore and experiment with other innovative approaches, as, for example, those based in the social-ecological systems (SES). In addition to provide guidance for formulating public policies and environmental management, the concept of complex, adaptive systems can build an understanding of simulation tools for the co-evolution of the biosphere and human cultures as social-ecological systems (Steffen et al. 2020).

Corollary

For most of the people, Patagonia has always evoked remoteness, vastness, wild nature, and wonderful landscapes. This narrative persists culturally today, but it clearly contrasts with the already observed unsustainable uses of its resources and environment; however, new economic opportunities, resources, and development emerge as future challenges. Many places on the Patagonian coast have potential for the establishment of energy, fishing, aquaculture, and tourism projects, and most of its wonderful landscapes are still seen as a destination of life for many people. However, the idea that this narrative of Patagonia could be questioned in the future has been growing from the scientific evidence that shows the results of overexploitation, pollution, environmental deterioration, and loss of habitats, along with the inability of their societies to reverse this trend.

The Patagonian coastal ecosystem is critically important to the Argentine economy, and human activities have already left their footprints on the environment, biodiversity, and landscapes. Experiences and learning from the Northern Hemisphere show us that Patagonia still has an opportunity to amend its historical problems and to prepare for the future challenges of GC as well. A task of this magnitude requires not only the reconstruction of the narrative and the effectiveness of the formally instituted governments but also a new form of governance that generates the empowerment of society.

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Correction to: Global Change in Atlantic Coastal Patagonian Ecosystems

**E. Walter Helbling, Maite A. Narvarte, Raúl A. González,
and Virginia E. Villafañe**

Correction to:
E. W. Helbling et al. (eds.), *Global Change in Atlantic Coastal Patagonian Ecosystems*, Natural and Social Sciences of Patagonia, https://doi.org/10.1007/978-3-030-86676-1

This book was inadvertently published with errors and the same has now been updated.

M. A. Narvarte and R. A. González’s affiliation was inadvertently tagged as Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Rawson, Chubut, Argentina for the introduction chapter. It has been corrected to read Consejo Nacional de Investigaciones Científcas y Técnicas (CONICET), San Antonio Oeste, Río Negro, Argentina.

Additionally, the editor’s name was mentioned as First name” E.” Last name” Walter Helbling”. It has been corrected to read “E. Walter” and “Helbling”.

The updated versions of the chapters can be found at
https://doi.org/10.1007/978-3-030-86676-1_1
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Copyright year was inadvertently published as 2021 and has been corrected to 2022.

The quote mentioned at the end of Introduction was inadvertently tagged to the chapter and has been corrected to reflect with part information.

"In calling up images of the past, I find that the plains of Patagonia frequently cross before my eyes; yet these plains are pronounced by all wretched and useless. They can be described only by negative characters; without habitations, without water, without trees, without mountains, they support merely a few dwarf plants. Why, then, and the case is not peculiar to myself, have these arid wastes taken so from a hold on my memory?" Charles Darwin (The voyage of the Beagle).

For chapter 5: M. A. Pagani's affiliation was inadvertently tagged as Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), La Plata, Buenos Aires, Argentina for the online version. It has been corrected to Consejo Nacional de Investigaciones Científcas y Técnicas (CONICET), Trelew, Chubut, Argentina.

For chapter 6: Maite A. Narvarte and Juan F. Saad's affiliations were inadvertently tagged as Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Rawson, Chubut, Argentina for the online version. It has been corrected to read Consejo Nacional de Investigaciones Científcas y Técnicas (CONICET), San Antonio Oeste, Río Negro, Argentina.

For Chapter 12: D. E. Galván's affiliation was inadvertently tagged as Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Rawson, Chubut, Argentina for the online version. It has been corrected to read Consejo Nacional de Investigaciones Científcas y Técnicas (CONICET), Puerto Madryn, Chubut, Argentina.

M. Varisco's affiliation was inadvertently tagged as Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Rawson, Chubut, Argentina for the online version. It has been corrected to read Consejo Nacional de Investigaciones Científcas y Técnicas (CONICET), Comodoro Rivadavia, Chubut, Argentina.

P. Martinetto's affiliation was inadvertently tagged as Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Rawson, Chubut, Argentina for the online version. It has been corrected to read Consejo Nacional de Investigaciones Científcas y Técnicas (CONICET), Mar del Plata, Buenos Aires, Argentina.

For Chapter 14: F. Tapella Consejo's affiliation was inadvertently tagged as Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), San Antonio Oeste, Río Negro, Argentina for the online version. It has been corrected to read Consejo Nacional de Investigaciones Científcas y Técnicas (CONICET), Ushuaia, Tierra del Fuego, Argentina.

For Chapter 17: V. E. Villafañe · E. W. Helbling's affiliations were inadvertently tagged as Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), San Antonio Oeste, Río Negro, Argentina for the online version. It has been corrected to read Consejo Nacional de Investigaciones Científcas y Técnicas (CONICET), Rawson, Chubut, Argentina.

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