Climate change impacts on the atmospheric circulation, ocean, and fisheries in the southwest South Atlantic Ocean: a review

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Abstract
We present an interdisciplinary review of the observed and projected variations in atmospheric and oceanic circulation within the southwestern South Atlantic focused on basin-scale processes driven by climate change, and their potential impact on the regional fisheries. The observed patterns of atmospheric circulation anomalies are consistent with anthropogenic climate change. There is strong scientific evidence suggesting that the Brazil Current is intensifying and shifting southwards during the past decades in response to changes in near-surface wind patterns, leading to intense ocean warming along the path of the Brazil Current, the South Brazil Bight, and in the Río de la Plata. These changes are presumably responsible for the poleward shift of commercially important pelagic species in the region and the long-term shift from cold-water to warm-water species in industrial fisheries of Uruguay. Scientific and traditional knowledge shows that climate change is also affecting small-scale fisheries. Long-term records suggest that mass mortalities decimated harvested clam populations along coastal ecosystems of the region, leading to prolonged shellfishery closures. More frequent and intense harmful algal blooms together with unfavorable environmental conditions driven by climate change stressors affect coastal shellfisheries, impact economic revenues, and damage the livelihood of local communities. We identify future modelling needs to reduce uncertainty in the expected effects of climate change on marine fisheries. However, the paucity of fisheries data prevents a more effective assessment of the impact of climate change on fisheries and hampers the ability of governments and communities to adapt to these changes.

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1 Introduction

Climate impacts marine populations through a variety of ecological processes, including reproduction, growth, migration patterns, recruitment, and phenology (Stenseth et al. 2002; Cochrane et al. 2009; Byrne 2011). Warming, acidification, and deoxygenation are major climatic stressors of ocean ecosystems (Gruber 2011). Climate change could also affect the life cycle, yield, variability, seasonality, and distribution of marine species, which could strain already vulnerable coastal communities (Poloczanska et al. 2016; Pecl et al. 2017). Although ocean warming is inhomogeneous, a redistribution of species associated with warming has been reported (Pecl et al. 2017). Thus, a higher rate of ocean warming could affect the distribution, abundance, and life history traits of fish (Pauly and Cheung 2018) and invertebrates (McLachlan and Defeo 2018).

Fisheries have strong socioeconomic impacts, representing key contributions to food security and to the livelihoods of millions of people. Worldwide, fisheries have supplied food, created employment, and generated income and economic growth through harvesting, processing, and marketing fish. Fish and invertebrates, which represent most of the marine fisheries catches, are strongly dependent on oceanographic conditions (Pauly et al. 2002; Pörtner and Knust 2007). Climate change affects the global productivity of marine fisheries (Free et al. 2019), exacerbating the challenges marine life faces (e.g., overfishing, pollution, and habitat degradation). Warming and other climate change-related stressors alter the distribution, demography, and life history traits of exploited species, with direct fishery implications through changes in the quantity, quality, and prediction of catches (Brander 2007; Stock et al. 2011; Barange et al. 2018; Free et al. 2019), resulting in detrimental socioeconomic impacts (Sumaila et al. 2011; Free et al. 2019).

The southwest South Atlantic Ocean (SWAO) shelf extends from Cabo Frío (~22° S, Brazil) to the tip of Tierra del Fuego (55° S, Argentina) (Fig. 1). This region is one of the most biologically productive areas of the world ocean (Acha et al. 2004; Lutz et al. 2010). Its marine fisheries supply food and livelihoods to millions of people in Brazil, Argentina, and Uruguay. Marine fish landed per year in Argentina, Brazil, and Uruguay reached an average of 956,000 t during 2005–2015 and present an overall decreasing trend (Bertrand et al. 2018). Moreover, the SWAO ranked third in the percentage of unsustainable stocks (59%) among the 16 major statistical areas identified by the FAO (2018). The declining catch pattern, together with the high percentage of stocks fished at biologically unsustainable levels, suggests a worrying scenario that could be associated not only with the fishing process itself but also with environmental fluctuations, which could impact fish stocks. The SWAO presents one of the largest marine warming hotspots worldwide (Hobday and Pecl 2014) and high-resolution models project sea surface temperature (SST) will continue to rise by at least 3 °C by 2099 (Popova et al. 2016).

Climate change has a significant impact on the ocean environment, such as warming (Roemmich et al. 2015), acidification, changes in stratification, circulation, and deoxygenation, among others. These changes impact the global distribution of marine biota, food security, and human wellbeing (Pecl et al. 2017).
Here we review observed and projected impacts of climate change on the atmospheric circulation, ocean, and fisheries of the SWAO. Projections for the regional climate and ocean are also described to discuss how future climate scenarios could impact regional fisheries.

2 The southwest South Atlantic Ocean

The SWAO is one of the most productive areas of the world ocean, mainly localized in the Patagonian continental shelf (Acha et al. 2004) (Fig. 1). The northern shelf is occupied by southward flowing Subtropical Shelf Water (STSW). STSW is composed by modified Tropical Water (TW) diluted by continental runoff from the coast of southern Brazil (e.g., Piola et al. 2000). TW intrusions are also observed in upper layers in the northern continental shelf. TW is part of the southward flowing Brazil Current (BC) along the shelf break, and it is the warmest shallow water in the region (Campos et al. 1995), whereas the South Atlantic Central Water (SACW) is observed below 200-m depth.

The southern shelf is mostly occupied by a relatively cold and fresh variety of northward flowing subantarctic waters, referred to as Subantarctic Shelf Water (SASW). SASW waters are exported offshore mainly near the region of confluence between the intense Brazil and Malvinas currents (Franco et al. 2018), which sweep the offshore edge of the shelf (Fig. 1). The Río de la Plata (RdP) discharge is the major freshwater inflow, with annual averages of ~23,300 m$^3$ s$^{-1}$. The Patos/Mirim Lagoon system (~32° S) also contributes an additional 1500 and 2000 m$^3$ s$^{-1}$ discharge (Möller 1996). Both discharges contribute to the formation of a low-salinity plume referred to as Plata Plume Water (PPW; e.g., Piola et al. 2008a). The PPW spreads along the coastlines of Argentina, Uruguay, and southern Brazil (Piola et al. 2000), and is exported to the deep ocean along the Brazil-Malvinas Confluence (Guerrero et al. 2014; Matano et al. 2014). Temperature and salinity distributions in the region are largely controlled by local atmospheric conditions, and remotely by regional- and global-scale climate variability modes (Barreiro et al. 2018). Large amplitude variations in continental runoff and low-level winds at seasonal and interannual time scales induce significant changes in the distribution of shelf water masses (Piola et al. 2005) and the shelf-deep ocean exchanges (Guerrero et al. 2014). These variations in RdP discharge modulate the input and distribution of freshwater and nutrients, which lead to large changes in water mass properties over the neighboring continental shelf (Ciotti et al. 1995; Piola et al. 2008a) and impact the spawning, recruitment, and feeding of the most abundant pelagic fishes (Acha et al. 2012; Checkley et al. 2017). Thus, continental runoff variability driven by atmospheric surface circulation regulates the recruitment variability in the outer estuary and affects the marine food web and fisheries over the shelf.

3 Climate change impacts on the atmospheric circulation, ocean, and fisheries

3.1 Atmospheric circulation

The atmospheric circulation over the South Atlantic Ocean (SAO) has changed during the past decades (Son et al. 2018; Yang et al. 2020). In austral summer, anthropogenically forced
stratospheric ozone depletion led to the poleward shift of the westerly jet and precipitation bands over the Southern Hemisphere. Moreover, a wider tropical belt and Hadley cell shift in response to increasing atmospheric greenhouse gas concentrations (GHG) have also been observed (Tao et al. 2016). A southward shift of the poleward edge of the Hadley cell during the past 30 years is also observed in control simulations of the fifth phase of the Coupled Model Intercomparison Project (CMIP5; Kim et al. 2017). Such changes in the Hadley circulation (e.g., width and strength) were not significant in pre-industrial control runs (Hu et al. 2013), suggesting that a substantial part of these changes is anthropogenic. This is also
consistent with the recent report of a poleward shift of the mid-latitude anticyclone in the SAO during the past four decades (Yang et al. 2020), inducing long-term changes in wind stress and wind stress curl over the SAO (Vizy and Cook 2016).

A significant positive trend in rainfall has been detected over the RdIP basin, particularly during summertime (Liebmann et al. 2004), which is partially attributed to human-induced increasing GHG (Vera and Diaz 2015). The increased precipitation leads to increased river runoff, which impacts the stratification (Piola et al. 2000) and circulation (Matano et al. 2014), and modulates the nutrient supply to the coastal ocean (Ciotti et al. 1995). Such changes in atmospheric forcing and river discharge may also have a substantial impact on recruitment of commercially exploited species (e.g., Acha et al. 2012; García-Alonso et al. 2019).

3.2 Ocean

Changes in surface winds and continental discharge are expected to have a strong impact on ocean stratification and circulation patterns, particularly over the shallow continental shelves (Combes and Matano 2018). Therefore, it is critical to understand the ocean response to changes in wind forcing and the variability of the continental discharge.

The sensitivity of the SWAO shelf circulation to changes in wind pattern is highest in the 28° S–35° S latitude band. Analyses of in situ observations (Piola et al. 2000), satellite observations (Piola et al. 2008b; Strub et al. 2015), and numerical models (Palma et al. 2008; Matano et al. 2014) show that seasonal reversals of the shelf circulation occur in this region in response to along-shelf wind reversals, from southwesterly in austral fall-winter to northeasterly in spring-summer. These seasonal reversals in the shelf circulation induce a northeastward extension of the low-salinity/high-nutrient PPW, and its southwestward retreat in spring-summer (Piola et al. 2000; Möller et al. 2008). The wind seasonality decreases south of 40° S, a region dominated by prevailing westerly winds throughout the year (Palma et al. 2008).

The poleward displacement in wind patterns reported during the past decades over the SAO (see Section 3.1) has led to a southward expansion of the subtropical gyre and the southward extension of the BC, leading to a wide region of positive SST trend (Goni et al. 2011; Lumpkin and Garzoli 2011). The BC warming over the past decades (Wu et al. 2012; Yang et al. 2016) created one of the most extensive and intense warming hotspots in the global ocean (Hobday and Pecl 2014) (Fig. 2). This warming region extends along the BC path, the South Brazil Bight (SBB, ~21° S–29° S), and in the RdIP. The latter is a distinct region of intense warming not well detected in global analyses. A detailed view of the temperature distribution trends in the region emerges from the analysis of higher spatial resolution observations (0.25° × 0.25°) from Oliver et al. (2018; their Fig. 1k).

Though the variability of along-shore winds determines the distribution of PPW over the shelf of southern Brazil and Uruguay, the availability of nutrient-rich freshwater is modulated by the variations of RdIP discharge. Positive ENSO phases lead to higher than average precipitation over the RdIP basin (Grimm et al. 2000) and hence a higher discharge (Cavalcanti et al. 2015). However, hydrographic (Piola et al. 2000) and satellite observations (Piola et al. 2008b), and numerical models (Matano et al. 2014) suggest that northeasterly winds prevail during periods of enhanced discharge, preventing the northeastward growth of the PPW.

South of 40° S, the shelf circulation is primarily forced by strong westerly winds, tidal currents, and the influence of the Malvinas Current, which flows northward along the upper
The northern portion of the shelf presents a large seasonal stratification cycle, which decreases further south in response to decreased net heat gain through the surface and increased wind intensity (Rivas and Piola 2002). The few direct current observations available (Rivas 1997; Valla and Piola 2015; Lago et al. 2019) and numerical models (Palma et al. 2008; Combes and Matano 2018) indicate a northeastward mean flow with increasing intensity towards the shelf break. Similar to what is observed further north, the variability in magnitude of the shelf transport south of the RdIP is primarily controlled by variations of along-shore winds (Lago et al. 2019).

Close to the coast, the circulation presents strong semi-diurnal fluctuations associated with the lunar tidal forcing. In agreement with observations, numerical simulations forced with different wind fields show a strong sensitivity of the shelf circulation to wind forcing (Palma et al. 2004; Combes and Matano 2018). Though most of the Patagonia shelf is under the influence of strong westerly winds, variations in the meridional wind stress can modulate the strength of the along-shore transport and the shelf break upwelling (Carranza et al. 2017; 2018).

Fig. 2  Overlap between the distribution of the large SWAO “hotspot” reported by Hobday and Pecl (2014) (data provided by A. Hobday, polygon with blue stippling), representing observed warming from 1950 to 1999, and difference between the mean 2000–2016 SST and 1982–1998 SST (reproduction of Fig. 1k of Oliver et al. 2018). Color shading and color scale at right
Combes and Matano 2018). The detection of these changes requires a robust, purposefully
designed network of in situ and remote observations.

3.3 Fisheries

The anchovy *Engraulis anchoita* is the most abundant forage fish in the SWAO. With a
maximum estimated biomass of 5.4 million t (e.g., Checkley et al. 2017), *E. anchoita* is
distributed from ~22° S to ~47° S (Hansen 2004). Adult stock displacements from
Uruguayan and Argentine shelves to southern Brazil follow diluted subantarctic waters
(Costa et al. 2016). Decreasing trends in egg abundance, a proxy of *E. anchoita*
biomass, are correlated with positive SST anomalies and high salinity conditions in
the northern Argentine shelf (Auad and Martos 2012). Off southern Brazil, egg and
larval abundance of anchovy are also negatively correlated with temperature fluctua-
tions (del Favero et al. 2018). A long-term analysis (1991–2017) also revealed a
declining trend in Argentine anchovy landings (34°–41° S), together with a decrease
in the size and weight at age (Prenski et al. 2016 and references therein). The stock
has been managed sustainably over time, with catches substantially below the total
allowable catch estimated by routine scientific hydroacoustic assessments, and the
fishery has been certified by the Marine Stewardship Council since 2011 (Pérez-
Ramírez et al. 2016). Therefore, climate change drivers influencing the oceanographic
conditions over the SWAO may be a major cause of the long-term trends in anchovy landings
(Supplementary Table S1). Similar trends in small pelagic fishes have been reported in the
northern hemisphere (Van Beveren et al. 2016; Saraux et al. 2019).

The Atlantic chub mackerel (*Scomber colias*) is a middle-size pelagic with a wide range
latitudinal distribution in the western Atlantic (45° N to 45° S; Eschmeyer et al. 2017; Alcaraz
2016). During the past decades (1991–2018), in austral summer, the distribution of this species
has expanded southwards up to 47° 30′ S (C Buratti, personal communication). This poleward
shift could be associated with a similar expansion of feeding grounds of large zooplankton,
mainly calanoid copepods (Cepeda et al. 2018; Supplementary Table S1). Similar poleward
expansions of the congeneric *S. scombrus* and *S. japonicus* have been reported in the Northern
Hemisphere in recent years. These displacements could be driven by shifts in food availability
and distribution, which, in turn, would respond to increased SST (Bruge et al. 2016; Pacariz
et al. 2016; Lee et al. 2018).

Impacts of long-term ocean warming on Uruguayan industrial fisheries have been recently
documented (Gianelli et al. 2019b). The mean temperature of the catch (MTC) over the
Uruguayan shelf, which is useful to assess global warming effects on fisheries (Cheung
et al. 2013), was significantly correlated with SST variability over the region (Gianelli et al.
2019b). The study suggests a shift from cold-water to warm-water species in landing com-
position from 1973 to 2017 (Fig. 3). The analysis also showed that landings of Argentine hake
*Merluccius hubbsi* strongly modulate the MTC trends. *Merluccius hubbsi* represented the most
important fishery in Uruguay during the past 60 years, and declines in catch per unit of effort
(Lorenzo and Defeo 2015), and landings (Gianelli and Defeo 2017) were observed in the past
25 years. *M. hubbsi* is a cold-water affinity species, and therefore, the systematic increase in
SST reported during the past 30 years over the Uruguayan shelf (Ortega et al. 2012, 2016)
implies a trend towards unfavorable thermal conditions for the species. The reported long-term
warming possibly exacerbated exploitation patterns responsible for the observed landing
trends (Supplementary Table S1). Due to the commercial relevance of the species and current
unfavorable thermal conditions over the Uruguayan shelf, a contraction in the trailing range edge of *M. hubbsi can be expected.

The Brazilian sardine (*Sardinella brasiliensis*), a small pelagic fish with biomass estimates up to 1.2 million t (Checkley et al. 2017), has been the main resource in the southeastern Brazil seine fishery (23°–29° S) during the past several years. At the main fishery ground in the SBB, the Brazilian sardine experienced a considerable decline in the 1980s due to overfishing (Jablonski 2007; Araújo et al. 2018). A poleward displacement of the shoals led to an increase in landings of the southern fleets from 1980 onwards (Jablonski 2007). Gasalla et al. (2017) also suggested that the Brazilian sardine moved to colder and deeper waters, leading to a southward shift in its distribution. The southern edge of the sardine distribution was typically at 29° S (Santa Marta Grande Cape), but the first occurrence of this species in southern Brazilian waters at about 34° S was reported in April–May 1991. More recently (2016–2017), sardine juveniles have been regularly caught on shallow waters (up to 30 m depth) at 31°–33° S during several research surveys (Catalani 2017), suggesting a persistent southward shift of its distribution during the past 20–30 years that may be associated with the intensification and poleward shift of the BC (Supplementary Table S1).

Long-term observations on estuaries and sandy beaches at Sepetiba Bay (~23° S), which serve as rearing grounds for commercially important fishes such as *S. brasiliensis*, suggest that boundaries of fish fauna distribution may have displaced poleward (Araújo et al. 2018), presumably in response to ocean warming (Supplementary Table S1). Changes in the presence and relative abundance of species over four decades (1980–2010) suggest that the region is facing a “tropicalization” of the marine community. Some small pelagic clupeoids (*Sardinella brasiliensis*, *Anchoa lyolepis*, *Anchoa tricolor*, and *Harengula clupeola*) responded to ocean warming with faster population growth rates, whereas others (*Anchoa marinii*, *Anchoviella brewirostris*, *Anchoviella lepidentostole*, and *Lycengraulis grossidens*) disappeared or
drastically decreased their abundance. The plausibility of the “tropicalization” process in the region is in agreement with the poleward expansion of tropical fish (Vergés et al. 2014).

The yellow clam *Mesodesma mactroides* is an intertidal bivalve with cold-water affinities that has been commercially exploited in sandy shores of Argentina, Uruguay, and southern Brazil (McLachlan and Defeo 2018). The yellow clam populations, and associated small-scale fisheries, have been affected by mass mortality events (Defeo et al. 2018), which expanded poleward, occurring first in 1993 in southern Brazil, reaching Uruguay in 1994/1995 and Argentina between 1995 (36° S) and 2002 (40.5° S; Ortega et al. 2016). Mortalities were observed mostly in spring and summer when clams are more susceptible to diseases. A decrease in abundance and individual size, together with a deteriorated body condition, has been documented in the long term and was associated with ocean warming during the past 30 years (Ortega et al. 2012, 2016). The yellow clam fishery has been closed during 14 years in Uruguay and is still closed in Argentina and Brazil, affecting economic incomes and local community livelihoods (Gianelli et al. 2015). Clam populations have not recovered to pre-mass mortality abundance levels, denoting a high sensitivity to warming and a poor adaptive capacity (Schoeman et al. 2014). The increase in frequency and duration of harmful algal blooms (HABs), a climate-driven stressor, adversely affects yellow clam fishing activities. An increasing representation of phytoplankton species with warm-water affinities and closely linked to warming along the Uruguayan coast has been documented (Martínez et al. 2017). The number of yellow clam fishery closures due to HABs increased from 30 days in 2014 to a total closure during the 2017 fishing season. In addition, more intense and frequent onshore southerly winds, another climate-driven stressor, restricted the number of fishable days in recent years (Gianelli et al. 2019a). The increasing adverse effect of red tides and unfavorable environmental conditions strongly impacted the yellow clam fishery, leading to loss of fishers’ revenues and economic uncertainty (Supplementary Table S1; Gianelli et al. 2019a).

Fishers also perceived that climate change in the SWAO affects their fisheries. In the SBB, fishers identified several climate-related signals such as reduced precipitation, increased drought and ocean temperature, calmer sea conditions, and changes in wind intensity and direction (Martins and Gasalla 2018). Many of the perceived changes, which have had overall negative effects on fishing activities, were supported by scientific long-term data (Martins and Gasalla 2018). In Uruguay, yellow clam fishers have expressed their concerns about the increase in HABs and the occurrence of mass mortalities (Pittman et al. 2019). They also perceived a significant reduction of fishable days through time due to unfavorable onshore wind conditions, an observation also scientifically verified (Gianelli et al. 2019a).

4 Projections on climate, ocean, and fisheries

4.1 Climate

Climate projections for the next decades forced by different increasing GHG scenarios suggest further widening of the Hadley circulation and a poleward displacement of the Southern Hemisphere westerlies (Tao et al. 2016). However, the recovery of stratospheric ozone concentration expected by around 2050 will slow down the poleward side of the upper tropospheric jet during summer (Tao et al. 2016). In contrast, some models suggest that ozone recovery will have no impact on surface winds (Karpechko et al. 2010). Trends in the observed zonal near-surface wind during the past 40 years (1979–2018) are consistent with climate
projections for the 21st (CMIP5) (based on Representative Concentration Pathway (RCP) of greenhouse gas emission scenario RCP4.5), suggesting the poleward shift of the subtropical anticyclone of the SAO based on anthropogenic forcing will continue (Fig. 4).

Future changes in precipitation may impact directly on continental discharge and ocean stratification, thus modulating nutrient fluxes into the coastal ocean. Globally, changes in rainfall over the oceans due to anthropogenic forcing follow in general the wet-gets-wetter, dry-gets-drier paradigm, with precipitation increasing in the equatorial regions, decreasing in the subtropics, and increasing again at high latitudes. In the SAO, rainfall is expected to decrease north of 30° S and increase further south, with a maximum in the SWAO. Annual precipitation extremes are expected to increase in subtropical South America and the SWAO (+ 15%). Models tend to agree on a projected summer rainfall increase of ~20–30% over southeastern South America. In winter, projected rainfall increases are ~10–20%, though these projections have large uncertainty (Sánchez et al. 2015).

Temperature projections for 2100 show an overall increase over South America during all seasons, with a 1.5–3 °C warming in the subtropical region (Sánchez et al. 2015). Climate models also project a positive trend in temperature extremes over the SAO (+ 1.0–2.0 °C) and neighboring continents (+ 2.0–4.0 °C) under a 2.0 °C global mean warming (Hoegh-Guldberg et al. 2018).

The SWAO is also affected by ENSO by inducing changes in surface winds, heat fluxes, and river discharges (Piola et al. 2005; Barreiro 2010). In a warming climate, an increased frequency of extreme rainfall events is projected during ENSO, accompanied by a decline in the frequency of weak or moderate daily precipitation, thus having limited impact on

![Observational climatology (contours) and trends (shading) of the zonal component of near-surface winds. Ensemble trends of the zonal near-surface winds are based on the NCEP/NCAR, NCEP/DOE, and ERA-Interim reanalysis datasets covering 1979–2018. Stippling indicates regions where trends exceed the 95% confidence level (Student’s t test).](#)

![Multimodel ensemble climatology (contours) and trends (shading) of the zonal component of near-surface winds. Contours indicate the climatology of zonal near-surface wind during the past 100 years of the pi-control experiment from CMIP5. Shading shows the zonal wind difference between the 2090–2100 RCP4.5 simulations and the past 100 years of the pi-control experiment. The 17 CMIP5 models used in the multimodel ensemble are listed below panel b. Stippling indicates regions where the difference exceeds one standard deviation of the local variations.](#)
seasonal mean rainfall anomalies (Cavalcanti et al. 2015). However, there is large uncertainty about the future characteristics of ENSO in a warmer climate and thus on how it may impact remote areas (IPCC 2013).

Mean circulation changes, like the latitudinal location of the jet stream, will affect the atmospheric teleconnections from the Pacific. Moreover, the climate variability will also change under global warming affecting southeastern South America (Martín-Gómez and Barreiro 2017). The impact of ENSO on southeastern South America is also modulated by the tropical Atlantic SST (Pezzi and Cavalcanti 2001; Barreiro and Tippmann 2008).

4.2 Ocean

Air-sea interactions play a key role in determining the climate and its variability in the SAO, where there is a long-term enhancement and a poleward shift of the subtropical anticyclonic flow (see Section 3.1). Consequently, the meridional shear of zonal wind between mid (south of 20° S) and high latitudes becomes stronger, increasing the wind stress curl and thereby inducing a stronger BC. Projections by 2100 (RCP4.5) based on a multimodel ensemble of 27 (CMIP5) simulations show that the stronger warming trend observed over the BC and its southern extension during the past decades (see Section 3.2) will continue (Yang et al. 2016). Yang et al. (2016) pointed out that changes in BC intensity and location in the twenty-first century will be largely controlled by the opposing effects of ozone recovery, rising GHG, and natural variability.

Anthropogenic changes in ocean circulation have been proposed as an additional stressor of marine ecosystems besides ocean warming or acidification, since large changes in the strength and position of the western boundary currents (i.e., the BC) have already been observed (Van Gennip et al. 2017). Projections by 2099 from a high-resolution global ocean model run under the IPCC strong warming RCP8.5 scenario show a weaker BC, in contrast with results based on lower resolution CMIP5 models (e.g., Yang et al. 2016). A southward displacement of the BC may arguably impact the nutrient supply from the Malvinas Current to the northern Patagonia continental shelf, with yet undetermined impacts on marine productivity and the marine food web, including fish.

To overcome the high uncertainty levels associated with predictions of global models and to gain better understanding of the changes in the circulation over the SWAO shelf, regional coupled ocean-atmosphere models with higher horizontal resolution than CMIP5-class models (1° × 1°) should be developed.

4.3 Fisheries

Projections of changes in fisheries catches under expected future climate change scenarios (based on RCP2.6 and RCP8.5) by 2050 and 2100 relative to 2000 in the EEZs of Argentina, Uruguay, and Brazil have been recently reported in terms of the total maximum catch potential (Cheung et al. 2018). The results based on outputs from the dynamic bioclimate envelope model (DBEM) (Cheung et al. 2016) and the dynamic size-based food web model (Blanchard et al. 2012) are shown in Fig. 5. Both models predict a decrease in overall fisheries catches for the three countries by 2050 and 2100 and for both climate change scenarios. Projections have very large uncertainties, mainly for Uruguay: averaged declines of $-10.43\% \pm 46.02\%$ and $-17.65\% \pm 53.24\%$ are predicted for the dynamic bioclimate envelope model by 2050 and 2100 (RCP8.5), respectively.
In the SWAO, commercially important species could be vulnerable to future climate scenarios (see details in Section 3.3). On global rankings, Argentina, Brazil, and Uruguay exhibited relatively low fishery vulnerability levels to climate change (Blasiak et al. 2017; Ding et al. 2017). Nevertheless, Brazil showed an index of vulnerability 2.5 times higher than Uruguay and Argentina, the latter being among the five least vulnerable countries across different RCPs and timeframes worldwide (Blasiak et al. 2017). Regional heterogeneity concerning vulnerability should be carefully considered. Worldwide, international conflicts between countries have arisen from shifts in fish stock distributions even in the presence of strong regional management governance bodies, suggesting the need for the development of new management tools to manage shifting resources (Pinsky et al. 2018).

Marine ecosystem services, including fisheries, are vulnerable to extreme weather events such as marine heatwaves. To date, the most intense marine heatwave in the SWAO shelf over the past 30 years left tons of dead fish and HABs on the Uruguayan coast during the austral
summer of 2017 (Manta et al. 2018). These events are projected to intensify and to occur more frequently in forthcoming years (Oliver et al. 2018), with a great potential to devastate marine ecosystems and impact the fisheries sector, increasing its vulnerability.

5 Conclusions and perspectives

Climate change has impacted the subtropical anticyclonic gyre over the SAO during the past decades, inducing long-term changes in wind stress and wind stress curl (Vizy and Cook 2016). Climate projections for the twenty-first century over the SAO based on anthropogenic forcing (RCP4.5) predict similar trends as have been observed during the past 40 years, suggesting that the poleward shift of the subtropical anticyclone of the SAO will continue.

Wind stress curl changes over the SAO have led to a BC intensification and poleward shift during the past decades. Consequently, intense ocean warming in the SWAO has been observed along the BC path, over the SBB shelf and in the RdIP. Detection of circulation changes over the SWAO shelf requires a robust, purposefully designed network of in situ and remote observations. Projections of changes in BC intensity and meridional shifts and climate-driven changes in ocean circulation will depend on climate conditions in the next decades (Yang et al. 2016). Higher resolution regional coupled ocean-atmosphere and biogeochemical models are required to unravel the impacts of atmospheric and ocean variability on the marine biota over the continental shelf.

Annual precipitation extremes are expected to increase mainly over subtropical South America and over the SWAO (+15%) (Hoegh-Guldberg et al. 2018). According to this projection, increased RdIP discharge, nutrient availability, and development of the PW can be expected over the inner shelf. These changes may provide more adequate conditions for spawning, recruitment, and feeding of fish in the region (Checkley et al. 2017) but may also be detrimental to species spawning in the outer estuary (e.g., Micropogonias furnieri; Acha et al. 2012). Further research is required to better understand how changes in freshwater input effectively impact regional fisheries.

Changes in fish fauna composition reported in the near-shore region of SE Brazil suggest that this region is facing a “tropicalization” of the marine community (Araújo et al. 2018). Likewise, Uruguayan industrial fisheries landings show a long-term increase in the relative representation of species that inhabit a warmer thermal niche, concurrent with a systematic increase in SST. *M. hubbsi*, a cold-water species that represents the most important fishery in Uruguay and the second most important in Argentina, has also exhibited decreasing landings during the past 25 years (Gianelli et al. 2019b). A poleward shift in the trailing range edge of *M. hubbsi* is expected as a response to warming, deserving urgent research efforts. Likewise, the poleward shift of the BC front may also result in a similar shift of the leading edge for *Sardinella brasiliensis*.

Climate change has also intensified extreme weather and climate events in the SWAO, to which small-scale fisheries are particularly vulnerable. The occurrence of mass mortalities in yellow clam populations and the subsequent lasting decline in abundance have severely affected the livelihoods of local communities along the coastlines of Brazil, Uruguay, and Argentina. In addition, HABs intensification, both in duration and frequency, threatens the economic viability of shellfisheries.

Under projected climate change scenarios RCP2.6 and RCP8.5, fisheries catches for the three countries are predicted to decrease through 2050 and 2100 (Cheung et al. 2018). Regional
projections have a high degree of uncertainty (mainly for Uruguay) and suggest a higher vulnerability for Brazilian fisheries. The alarming lack of long-term information on fisheries has also affected global analyses and predictions. Moreover, small-scale fisheries are not well represented in these global models. Projections of changes in fisheries catches for the SWAO require urgent research efforts based on observations of changes in yield, abundance, distribution, and individual sizes of the main fisheries resources. The impact of such projected changes will depend on how the countries in the region increase their adaptive capacity to climate change.

The evidence presented here unambiguously shows that SWAO fisheries have rarely been addressed from a climate change perspective. Brazil, Uruguay, and Argentina host numerous commercially significant fisheries and the studies summarized in this review represent the current state of the art of the knowledge about fisheries and climate change in the region. Lack of long-term monitoring programs, restricted access to available information, partial data upload to global databases of stock assessments, and institutional indifference to consider environmental shifts in fisheries management have all contributed to a knowledge-poor situation compared with other regions. This asymmetry has (1) proved evident in meta-analysis studies (Poloczanska et al. 2016); (2) influenced global efforts to forecast future impacts of climate change on fish populations (Barange et al. 2018); and (3) hindered the analysis of the historical impact of ocean warming on marine fisheries production (Free et al. 2019). The data scarcity leads to a poor representation of the SWAO in global assessments of the climate impact on fisheries and undermines the adaptive capacity of governments and dependent marine communities. In a region where 59% of assessed stocks are fished at unsustainable levels, improved assessments could set the basis to establish better fisheries management strategies. Rigorous vulnerability assessments of marine fisheries to climate change are needed to minimize socioeconomic risks associated with climate-driven changes in abundance and distribution of marine fish species. By raising awareness of the potential impact of climate change on fisheries, adapting to changes in fisheries yields, and proactively creating effective transboundary institutions, many of the potential detrimental climate change effects on fisheries could be alleviated (Gaines et al. 2018; Pinsky et al. 2018).

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