Evidence of ocean warming in Uruguay's fisheries landings: The mean temperature of the catch approach

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Running page head: Uruguayan fisheries in a changing climate

Abstract

Distribution, abundance and life history traits of marine fish and invertebrates are increasingly affected by ocean warming. Consequently, landings of traditional fisheries and their relative species composition could potentially be modified. The mean temperature of the catch (MTC) concept, which refers to the average inferred temperature preference of exploited species weighted by their annual catch for a given area, was applied to Uruguay's industrial fisheries. This approach allowed assessing evidence of ocean warming in long-term Uruguayan landings (1973-2017), which were mostly obtained from a major marine warming hotspot. Results showed a marked shift in MTC through time, with the first 10-15 years characterized by a decreasing trend, but subsequently increasing steadily over time. Long-term effects of ocean warming have led to a shift from cool-water to warm-water species in the relative representation of local landings. A significant and consistent association between sea surface temperature and MTC increase was observed, even when accounting for other drivers. This study provides the first quantitative evidence supporting that ocean warming has been increasingly affecting Uruguayan industrial fisheries during the past decades and call for an urgent need to consider environmental changes to appropriately manage stocks, particularly those shared with neighboring countries.

Keywords: climate change; ocean warming; fisheries; mean temperature of the catch; Uruguay

Introduction

Ocean warming has profound and well documented impacts on fisheries (Perry et al. 2005, Hoegh-Guldberg & Bruno 2010, Free et al. 2019). The economy and the livelihood of communities who depend on marine resources for food security are being increasingly threatened by rising ocean temperature (Allison et al. 2009, Hobday et al. 2016). Marine species respond to ocean warming by altering their depth (Dulvy et al. 2008) and/or latitudinal range (Cheung et al. 2009, Pinsky et al. 2013), mostly shifting their distributional range poleward (Madin et al. 2012, Pecl et al. 2017). On a global scale, ocean warming has been inhomogeneous. Hobday & Pecl (2014) identified several marine hotspots, which are regions where the sea surface temperature (SST) has increased most rapidly over the period 1950-2000 and are projected to continue changing at a faster rate than the global average. As marine species respond to ocean warming (Pinsky et al. 2013), these hotspots could affect the distribution, abundance and life history traits of fish (Pauly & Cheung 2018) and invertebrates (McLachlan & Defeo 2018), thus affecting catch levels and fisheries targeting traditional resources. This situation is aggravated by the fact that marine fisheries constitute complex systems that are also influenced by human-induced changes such as exploitation history and management tools (Österblom et al. 2017). Thus, disentangling exploitation patterns from climate change effects represents a major challenge due to the interconnected nature of both drivers (Alheit et al. 2004).

Several approaches have been applied to understand and project impacts of climate change in fisheries (Barrange et al. 2010), although most of them fell short on critical aspects such as the role of management measures and resource use in aggravating or mitigating impacts (but see Costello 2018, Gaines et al. 2018). Cheung et al. (2013) developed an innovative and simple approach for assessing the signature of ocean warming in fisheries catches, based on the "mean temperature of the catch" (MTC), which refers to the average inferred temperature preference of exploited species weighted by their annual catch for a given area (e.g. Large Marine Ecosystems (LMEs) or Economic Exclusive Zones). The underlying ecological theory is that thermal preferences of marine species can be described by a Gaussian function with an optimal inferred temperature. Thus, an increase in MTC would indicate more warm-water species in the catch and/or a decrease in the amount of cool-water species. Recent analyses in the Mediterranean Sea (Tsikliras & Stergiou 2014) and China's seas (Liang et al. 2018) supported global observations about the increase in the MTC at a regional scale. Other studies used fishery-independent data to estimate and compare MTC results from those obtained using landings data (Keskin & Pauly 2014, Tsikliras et al. 2015), or took into account habitat characteristics and indirect measures of fishing effects (Maharaj et al. 2018, Tsikliras et al. 2019).

However, if not properly addressed, the MTC (based only on catch data) could lead to misleading conclusions. MTC analyses should also consider the effects of fishing effort, markets and industry portfolio diversifications, which can influence the relative composition of the catch.

In the Southwestern Atlantic Ocean (SAO), the continental shelf of southern Brazil, Uruguay and northern Argentina embraces one of the largest marine hotspots (Hobday & Pecl 2014). This oceanographic complex region is characterized by high seasonal variations modulated by the confluence of two water masses with different thermohaline characteristics (Matano et al. 2010, Piola et al. 2018). Subtropical warm waters are carried southward by the Brazil Current along the shelf break, while subantarctic cold waters are advected northwards by the Malvinas Current (Fig. 1). Their confluence is marked by an array of strongly contrasting water types (Gordon 1984) that define a very energetic and complex region (Fig. 1). Additionally, the Río de la Plata estuary, the major freshwater discharge in the area (average discharge of 22,000 m^3 s^{-1}; Guerrero et al. 1997), injects buoyancy and nutrients contributing to system complexity. Furthermore, El Niño Southern Oscillation (ENSO) has a pronounced effect in the area by altering precipitation regimes, which in turn modulate the Río de la Plata discharge magnitude (Piola et al. 2005, 2018). The effect of ENSO on SST anomalies (SSTA) in the SAO is less evident, though lagged northward extensions of cold water were related with ENSO cold phase and the opposite for ENSO warm phase (Colberg et al. 2004 and references therein; Ortega & Martínez 2007). Critically, but less understood, is the atmosphere-ocean coupling during ENSO events (Ortega & Martínez 2007, Barreiro 2009). This dynamic oceanographic setting, with a high degree of seasonal and interannual variations, determines a complex horizontal and vertical structure that provides favorable environmental conditions for high primary productivity and also for spawning and breeding of fish and invertebrate populations (Ciotti et al. 1995, Acha et al. 2004, Jaureguizar et al. 2016).

Several studies at a global scale have projected significant mid and long-term catch losses in the SAO (Cheung et al. 2009, Blanchard et al. 2017, Cheung et al. 2018), seriously threatening an already weakened Uruguayan and Argentinean industrial fishery sector (Villasante et al. 2016, Gianelli & Defeo 2017). The uncertainty of these global model projections at the regional scale is aggravated by the rapid changes in oceanographic conditions occurring in this hotspot. However, despite the importance and scope of this phenomenon for fisheries and dependent communities, to date there are few studies of the impact of climate change on fisheries in this region (Bertrand et al. 2018). Even more uncertain is the understanding of how environmental change and management policies could interact in aggravating or mitigating climate change impacts (Barange et al. 2010, Gaines et al. 2018). Additionally, the scarcity of fishery-independent data renders it difficult to disentangle multiple, potentially confounding factors, such as changes in fishing pressure, market effects and consumer preferences, from potential climate drivers (Madin et al. 2012, Ortega et al. 2012). Thus, there is an increasing need to provide meaningful evidences of climate change impacts on major fishery resources, with the explicit inclusion of the human dimension. Ideally, this will assist fishery industry and managers to develop adaptation and mitigation plans for regional fisheries in a changing climate.

In this paper we applied the MTC approach to long-term Uruguayan industrial fishery landings (1973-2017), which are mostly obtained from one of the most energetic and largest marine hotspots. An analysis of a variant of the MTC index was also carried out to account for the effect of the dominant species on the composition of the catch. Results were complemented with detailed Uruguayan and Argentinean fishery landings for the period 1996-2017, provided by the binational commission responsible for managing straddling fish stocks in the study area. Finally, the MTC index was modeled to assess the relative contribution of environmental variables and historical exploitation patterns of the Uruguayan fishing fleet.

Methods

The Uruguayan industrial fleet

The Uruguayan industrial fleet operates on the Río de la Plata estuary (the widest estuary in the world) and in the Argentinean-Uruguayan Common Fishing Zone (AUCFZ). This zone is determined by two arcs of circumference of 200 nm radius, centered at Punta del Este (Uruguay) and Punta Rasa (Argentina) (Fig. 1). The area of the AUCFZ is 218,718 km^2 and includes almost entirely the Uruguayan Exclusive Economic Zone (EEZ). The Joint Technical Commission of the Uruguayan-Argentinean Maritime Front (CTMFM for its acronym in Spanish) is the regional management and governance body responsible for compiling fishery statistics from both countries, coordinating research plans and performing joint stock assessments for most commercially important resources within the AUCFZ (see http://ctmfm.org/).

Industrial vessels operate, by law, beyond 7 nm from shore. Most Uruguayan vessels are bottom trawlers. Longlines and pots are used in a lesser extent to target pelagic and benthic resources, respectively. The industrial fishing sector has traditionally represented >95% of total Uruguayan landings and currently consists of 50–55 vessels (15–60 m length) with a mean of 360 Gross Tonnage. More than 50 species are caught by the Uruguayan industrial fishing fleet. However, landings of Argentine hake (*Merluccius hubbsi*), whitemouth croaker (*Micropogonias furnieri*) and stripped weakfish (*Cynoscion guatucupa*) historically represented more than 85% of total landings (Gianelli & Defeo 2017). Landings have drastically fluctuated in the long-term following the phases described by Gianelli & Defeo (2017): development, expansion, stabilization-diversification and a last phase of declining yields and market contraction.

Fisheries statistics and climatic data

Uruguayan landings within the AUCFZ[1] and the Río de la Plata estuary for the period 1973-2017 were extracted from the National Direction of Aquatic Resources (DINARA for its acronym in Spanish) reports (compiled in Gianelli & Defeo 2017: Fig. 2a). The analysis was conducted at the species level or at a higher taxonomic level in which we were confident of the predominance of a single species (e.g. *Mugil* spp. and *Squatina* spp.). This resulted in 21 species or genera representing 95% of total historical landings. The remaining landings reported in official records were aggregated into higher taxonomic resolution levels and were not considered in this paper. An additional MTC variant (Table 1) and analysis were performed by excluding species that comprised >20% of landings, following Maharaj et al. (2018). This approach allows MTC to be more representative of species assemblages, avoiding trends that are disproportionately affected by few dominant species.

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[1] Species targeted outside the AUCFZ were excluded from the analysis (i.e. high migratory tunas and billfishes).

The temperature preference for each species was obtained from two different sources: (1) Cheung et al. (2013), which inferred temperature preferences from the overlap of species distribution range maps with SST data (averaged of 1970 – 2000; see Jones et al. 2012 and Supplementary Online Material of Chueng et al. 2013 for methods); and (2) FishBase and Sea Life temperature preference data (Froese & Pauly 2011), based on the Aquamaps (www.aquamaps.org) approach, which uses descriptors of species relationships with environmental variables and expert judgment to predict spatial distributions from publicly available global occurrence databases. In order to assess if the data provided by Cheung et al. (2013) and FishBase were within the physiological temperature preference ranges derived from *in situ* samples in the region, we reviewed published papers and local grey literature. MTC was computed as the average of the temperature preference of exploited fishes and invertebrates species weighted by their annual catch (Cheung et al. 2013):

$$MTC_{yr} = \frac{\sum_i^n \mathbf{Ti\ Ci, yr}}{\sum_i^n \mathrm{Ci, yr}}$$

where *Ci, yr* is the catch of species *i* in year *yr*, *Ti* is the median temperature preference of species *i* (described by a Gaussian function) and *n* is the total number of species reported from landings within the AUCFZ. For visualization purposes, the MTC anomaly (relative to the 1973-2017 mean) is shown hereafter. The cumulative sum of annual MTC anomaly (MTCcs) was used to detect sustained shifts in the MTC index, marked by changes in slope of the cumulative sum plot (Fiedler 2002 and references therein).

SST and SSTA for the grid delimited by the coordinates 34.5-39° S and 52-58.5° W were obtained from the IRI/LDEO Climate Data Library (ridl.ldeo.columbia.edu 2018, Kalnay et al. 1996, Reynolds et al. 2002). SST and SSTA were calculated by averaging these variables over 4° x 3° grid cells of the SAO shelf and the adjacent oceanic region. The cumulative sum of annual mean SSTA (SSTAcs) was used to detect sustained shifts in climate, marked by changes in slope of the cumulative sum plot (Fiedler 2002).

Temporal pattern in the MTC and modeling

Segmented regression analyses were used to assess possible shifts in the MTC through time and to detect the breakpoints (year) when MTC changes occur. This procedure was applied to the MTC index considering all species and also excluding the dominant ones (Argentine hake and whitemouth croaker, Fig. 2a). Multiple linear regression models were also used to explore the relationship between the MTC index, the composition of the Uruguayan fishing fleet for each year and environmental effects (without and with time-lag up to three years). Environmental variables included SSTA and the Río de la Plata estuary discharge based on data reported by Borús et al. (2017). On the other hand, the utilization of different fishing métiers and strategies could stabilize fluctuations in fishing catches (Cline et al. 2017), while maintaining overall efficiency in utilization of fishery resources and ecosystem functioning (Zhou et al. 2010). Thus, based on vessels characteristics, targeted species and operation areas, an annual diversity index for the Uruguayan fleet (Simpson index) was estimated using data provided by Marín (2016) and DINARA reports (Fig. 2b). Variations in the Simpson index could account for major shifts in the diversification portfolio, switch in target species or specific fishery closures from one year to another.

Grounded on the provided background we established our main assumptions regarding the interaction between the MTC index and environmental and fishing effects, as follows: (1) due to the rapid changes in SST observed in this region, a clear sign of ocean warming in Uruguayan landings should be expected; (2) freshwater discharge anomalies could induce variations in the relative proportion of freshwater, brackish and marine species, leading to MTC changes; (3) fleet composition could be driven by market effects and portfolio diversification strategies, thus affecting catch composition and masking the effects of environmental change.

Prior to model fitting, all variables were standardized (z-scores). In the case of nested models, the selection was performed based on likelihood ratio tests and AIC for small samples. The final model was checked for temporal autocorrelation in the residuals (see Fig. S2 in the Supplement). All statistical analyses were performed using R version 3.5.2 (R Core Team 2018). It should be noted that other potential effects of ENSO oscillations on MTC variations were analyzed through several approaches without any concluding result (see Supplement). Therefore, we do not further discuss ENSO effects hereafter, but focus in its most obvious manifestations: the Río de la Plata discharge and SSTA (both directly and indirectly affected by ENSO conditions).

For the period 1996-2017, the CTMFM published landings data with detailed taxonomic resolution (28 species for Uruguay and 25 species for Argentina: Table 1). Thus, we re-estimated MTC for the period 1996-2017 based on CTMFM landings and compared with the previously described MTC time series (21 species for Uruguay for the period 1973-2017) through correlation analysis and paired samples t-tests. Because the CTMFM also compiled Argentinean landings, we estimated MTC for the entire AUCFZ (Uruguayan plus Argentinean landings for the period 1996-2017: Table 1) and compared with MTC estimated only for Uruguay.

Results

Segmented regression models showed a marked shift in MTC through time, being characterized by a decreasing trend from 1973 to 1985 and steady increase over time until 2017 (Fig. 3a). By removing the effect of the two dominant species (*Merluccius hubbsi* and *Micropogonias furnieri*), the previously observed directional change was reinforced, but the breakpoint occurred later in the record, in 1999 (Fig. 3b).

The regional SSTA increased steadily since the mid-1990s with a clear dominance of positive values after 1999 (relative to 1973-2017 climatology: Fig. 4a), a trend particularly noticeable in the temporal analysis of SSTAcs (Fig. 4b). MTC anomaly showed a similar pattern to SSTA (Fig. 4a), particularly after year 2000. The cumulative sum plot of MTC anomaly and SSTA (Fig 4b) showed a consistent and positive correlation ($r = 0.88$; $p < 0.01$) and a concurrent shift in the cumulative sum slope of both variables. Related changes in both regimes suggest a close association between SST and MTC. This pattern also suggests that between the mid-1990s and 2000 an oceanographic change occurred in the region, which modulated the MTC index including all species (Fig. 4a) and also excluding dominant ones (Fig. 3b).

Multiple linear models showed a close association between MTC, SSTA and fleet diversity, with and without time-lags (Table 2). The Río de la Plata discharge anomaly was only statistically significant when considering 1-year time-lag (Table 2). Based on the different coefficients of determination obtained for models with and without time-lags (Table 2) and for the sake of parsimony, we retained the model without time-lag. This model showed that SST and the Simpson index were significant predictors of MTC (Table 3; Fig. 5a and 5b). The Río de la Plata discharge anomaly was marginally non-significant ($p = 0.057$) and disregarded from the final model. MTC was positively related with SSTA and negatively related with the Simpson index (regression slopes: 0.43 and -0.44 respectively). The latter implies that, as a particular type of fleet dominated in a given year targeting one or a small group of species (low portfolio diversification), MTC decreased. On the other hand, MTC increased when the fleet was more heterogeneous (high portfolio diversification) and provided a more balanced catch composition. The almost equal normalized coefficients (with opposite signs) of SSTA and Simpson index denoted that both variables are equally important as MTC predictors (Table 3). The final model explained a significant amount of the variance ($R^2 = 0.63$) and model residuals did not show temporal autocorrelation (Fig. S2).

MTC estimated using CTMFM landings data for Uruguay (28 species) and the MTC based on Gianelli & Defeo (2017: 21 species) exhibited a significant and positive linear correlation ($r = 0.98$; $p < 0.01$) for the period 1996-2016. Although the directional pattern remained the same, the more detailed taxonomic resolution for Uruguayan landings registered by the CTMFM influenced the MTC index slightly. The t-test for paired samples showed that MTC based on CTMFM was slightly but significantly lower for the analyzed period ($t = -9.26$, $p < 0.001$). Additionally, the MTC based on Uruguayan and Argentinean landings (total landings for the AUCFZ) showed a significant linear increase through time ($R^2 = 0.77$, $p < 0.001$, Fig. 6a), consistently with the MTC pattern observed only for Uruguay for the 1973-2017 period (Fig. 6b).

Discussion

This study provides the first quantitative evidence supporting that ocean warming has been increasingly affecting Uruguayan industrial fisheries during the past decades. Long-term effects of climate change have led to a shift from cool-water to warm-water species in the relative representation of Uruguayan landings. Furthermore, a significant and consistent association between SST and MTC increase was observed, even when accounting for other drivers such as the composition of the fleet and the influence of freshwater input with large interannual variability. MTC, which symbolizes a sort of thermometer of annual landings, represents a first attempt to address climate change effects on fisheries in the SAO.

Our results suggest that the AUCFZ is a very vulnerable region to a warming scenario and provide evidence that the SAO system and its biota are responding consistently with expectations under ocean warming (Bertrand et al. 2018). The shift from a cold to a warm phase during the 1990s (Ortega et al. 2016), as well as the increase in speed and frequency of onshore (southeast) winds (Escobar et al. 2004, Bischoff 2005), could enhance the advection of warm waters from the Brazil Current to the southern Brazil and Uruguayan shelf. Indeed, Ortega et al. (2016) showed a poleward shift of the warm water front (20° C; a proxy of the front of tropical waters) of the order of 9 km yr^{-1}, which was positively correlated with the increase in SSTA, suggesting that ocean warming in this region may be related to changes in broader atmosphere and ocean circulation patterns. A similar southward displacement of the Brazil-Malvinas Confluence has been reported based on satellite and in-situ observations (Goni et al. 2011, Lumpkin & Garzoli 2011) and realistic numerical simulations (Combes & Matano 2014). Numerical simulations indicate that both the Brazil and the Malvinas currents play a significant role on the intensity of the shelf circulation (Palma et al. 2008, Matano et al. 2010). Thus, shifts in the Confluence may lead to significant changes in the circulation of the AUCFZ. Although the marine species that inhabit this region must be adapted and resilient to these oscillations in oceanographic conditions, the sustained increase in SSTA could lead to unprecedented changes in the composition and structure of ecological assemblages, including extensions/contractions of their geographical range (Horta e Costa et al. 2014). This long-term process may be preceded by an increase in the frequency of records of marine species with tropical affinities (Demicheli et al. 2006, Segura et al. 2009, Martínez et al. 2009, Izzo et al. 2010) and changes in the prevalence of cold water species towards warm/temperate water species (Schoeman et al. 2014; Lercari et al. 2018). These results taken together support the hypothesis of an increase in MTC in this subtropical region (Cheung et al. 2013) that aggravated the crisis of the Uruguayan fishery sector, which is mainly based on the Argentine hake fishery, a cool-water affinity species.

The geographical region analyzed here represents an ecotone between the LME of South Brazil and Patagonian Shelf. Transitional characteristics, both in oceanography and biodiversity, place the AUCFZ as a relevant system to assess the effects of climate change on the marine realm. Cheung et al. (2013) showed that the MTC in the South Brazil LME has been fluctuating in the past decades, whereas MTC in the Patagonian Shelf LME has been decreasing. Two main factors impact the environmental conditions in the AUCFZ. Firstly, variations in the along-shore wind stress modulate seasonal oscillations and the interannual distribution of the Río de la Plata plume (Simionato et al. 2001, Piola et al. 2005, Palma et al. 2008, Matano et al. 2014). In addition, the Subtropical Shelf Front (STSF, Piola et al. 2000) marks an intense subsurface transition between warm-salty subtropical shelf waters and cold-fresh subantarctic shelf waters. Both features exert a significant influence on the distribution of nutrients, suspended matter, zooplankton and ichthyoplankton in the AUCFZ (Ciotti et al. 1995, Muelbert et al. 2008), and seem to delineate the transition between the Patagonian Shelf and South Brazil LMEs. At interannual and longer time scales, the meridional fluctuations of the basin-scale wind fields that modulate the location of the Brazil-Malvinas Confluence may also impact on: (1) variations in the distribution of Río de la Plata waters; (2) the location of the STSF; and therefore (3) variations in SST that are reported in this study. Such changes would have a significant impact on the AUCFZ and the neighboring shelf ecosystem, suggesting that species inhabiting the boundaries of these LMEs should be resilient to variations, whereas species with trailing range edges of their geographical distribution should be especially vulnerable to climate change. Thus, the limits between these two LMEs could be much more dynamic than previously thought, affecting the geographic extension both for subantarctic and subtropical species.

The removal of dominant species from the analysis showed a marked influence of Argentine hake (cool-water affinity) and whitemouth croaker (warm-water affinity) landings in modulating MTC trends. Reduced catch per unit of effort (Lorenzo & Defeo 2015) and landings levels (Gianelli & Defeo 2017) in Argentine hake for the past 25 years have been largely attributed to a failure in the management system. However, climate change could be partially responsible for exacerbating the observed trends. Due to the commercial relevance of the region and its sustained increase in SST, a contraction in the trailing range edge of Argentine hake may be expected, deserving urgent research efforts. Furthermore, recent reports from a nearby region, conclude that the reproductive success indexes of Argentine hake are negatively correlated with SST, particularly in autumn (late larval or early juvenile phase: Marrari et al. 2018). On the other hand, the wide thermal niche of whitemouth croaker and its affinity for warm waters determine that this species may be less sensitive to an increase in regional SST. Other factors such as the Río de la Plata discharge and coastal pollution are more relevant for the biology of this species. Acha et al. (2012) have shown that high freshwater runoff events promote low retention of eggs and larvae, which would affect the reproductive success of this commercially important species. In addition, interannual variations of Río de la Plata discharge alter the position and distribution of frontal zones and of those species that use them for spawning, such as the whitemouth croaker (Jaureguizar et al. 2016). In this sense, it can be hypothesized that under high freshwater runoff conditions a greater spatial dispersion of whitemouth croaker will be observed and, therefore resulting in a lower catchability for the fishing fleet. The fact that the Río de la Plata discharge variations appear to be confined to the region close to the river mouth (Piola et al. 2008, Matano et al. 2014) could explain the marginal relationship between discharge and MTC (a community index). However, this predictor could be especially meaningful for brackish water species, such as the whitemouth croaker (Jaureguizar et al. 2016).

Managers and decision makers have left aside the effects of climate change in fisheries to focus on traditional fisheries management and the pressing threat of overfishing. However, this study suggests that there is a need to consider the effects of environmental changes to properly manage stocks located in a dynamic warming hotspot, particularly those shared by neighboring countries. The consistent results in MTC increase using different landing databases for the entire AUCFZ during 1996-2016 (considering Uruguayan and Argentinean landings) call for a regional cooperation strategy. As the responsible governance body, the CTMFM will have to deal with stock distributions becoming less predictable and traditional fisheries declining or new fisheries emerging. Existing fisheries management and governance schemes are largely based on the premise that fish stocks distribution ranges remain relatively static through time (Gutiérrez & Defeo 2013). However, as already observed in several regions and predicted at a global scale (Pinsky et al. 2018), many fish stocks will likely shift across national and other political boundaries in coming decades. Thus, cooperative management will play a critical role for facing conflicts over newly or no longer shared resources due to the effects of climate change in this region (Villasante & Österblom 2015).

Our study leaves open several issues related to: (1) strategies to be explored by the Uruguayan government and/or its industrial fishery sector to cope with changing oceans; (2) the need to carry out regional studies by incorporating detailed long-term Argentine landings data and including fishery independent surveys to provide robust lines of evidence for the AUCFZ; (3) the need to manage fish stocks based on model projections, not merely on historical and statical assumptions about the distribution and abundance of the species; and finally (4) assess the potential for regional multinational collaboration on fisheries and ocean sustainability issues. The later issue needs to be implemented on a scale large enough to capture the impacts of climate change on regional fisheries of the SAO.

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Figures

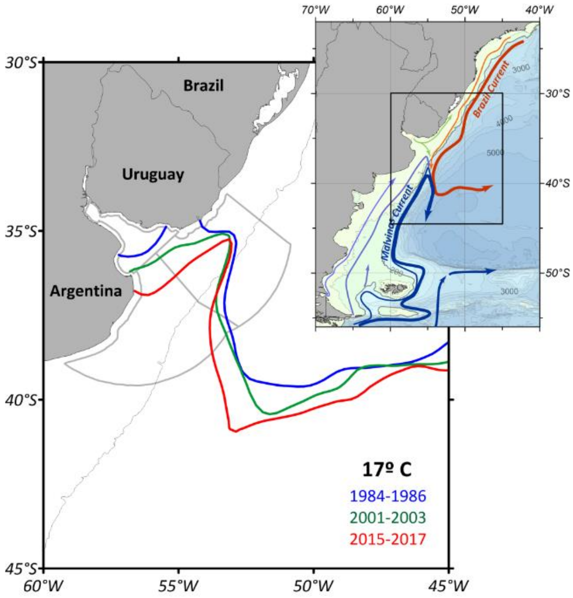

Fig. 1. Mean location of the 17 °C isotherm (proxy of the latitudinal shift of the warm waters front) derived from sea surface temperature (Reynolds et al. 2007) averaged for the periods 1984-1986 (blue), 2001-2003 (green), 2015-2017 (red). The Argentinean-Uruguayan Common Fishing Zone is delimited by the grey polygon. The 200 m isobath is highlighted in gray. The upper panel shows a schematic representation of major ocean currents in the Southwest Atlantic Ocean, with depth (m) indicated by background shading (adapted from Piola et al. 2018).

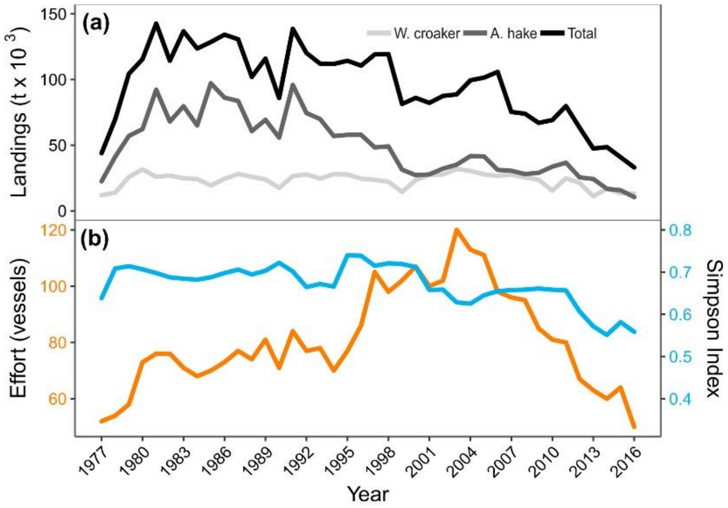

Fig. 2. Long-term (1977-2016) variations in: (a) Uruguayan industrial fleet landings (total and, specific for Argentine hake (A. hake) and whitemouth croaker (W. croaker:)); (b) fishing effort, expressed as the number of vessels operating each year (orange line) and Simpson's Index based on the composition of the fishing fleet (light blue line). Landings and fishing effort time series were not linearly correlated (r = 0.22, p = 0.17).

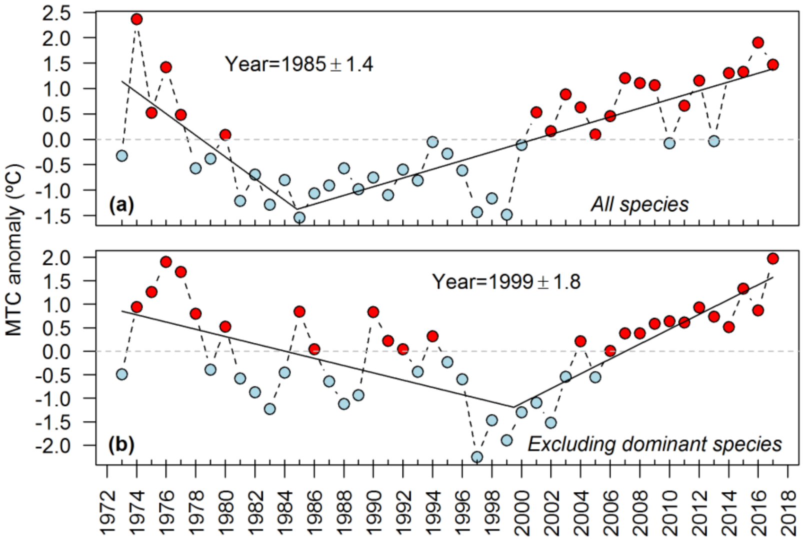

Fig. 3. Mean temperature of the catch (MTC; ºC) anomaly for Uruguayan landings (1973-2017) in the AUFCZ for (a) all species landed (n = 21; 95% of total landings); and (b) excluding *Merluccius hubbsi* and *Micropogonias furnieri,* which represent nearly 70% of historical landings. The linear fits of segmented regressions are shown to highlight the increase in MTC since (a) 1985 ($R^2 = 0.62$); and (b) 1999 ($R^2 = 0.52$). Red and light-blue dots represent positive and negatives anomalies in MTC, respectively.

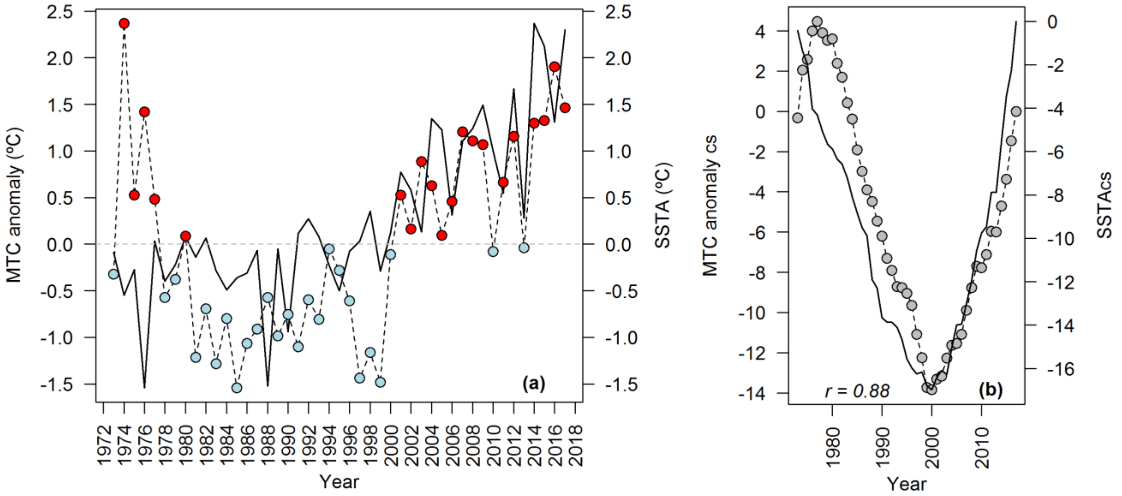

Fig. 4. Long-term variations (1973-2017) in: (a) annual mean temperature of the catch (MTC; ºC, dashed line) anomaly and sea surface temperature anomaly (SSTA in ºC; solid line). Red and light-blue dots represent positive and negatives anomalies in MTC, respectively; (b) cumulative sum of mean temperature of the catch anomaly (MTC anomaly cs; grey dots and dashed line) and sea surface temperature anomaly (SSTAcs; solid line).

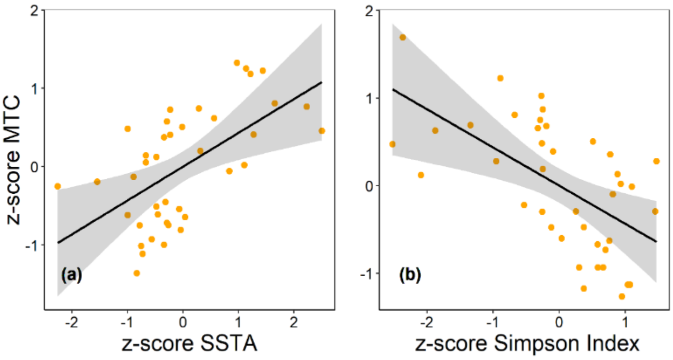

Fig. 5. Mean partial effects of: (a) sea surface temperature anomaly (z-score SSTA); and (b) Simpson index applied to the fishing fleet each year (z-score Simpson Index), in the mean temperature of the catch (z-score MTC). Gray shadows indicate the 95% confidence interval. All variables were standardized to allow comparisons of slopes between predictors.

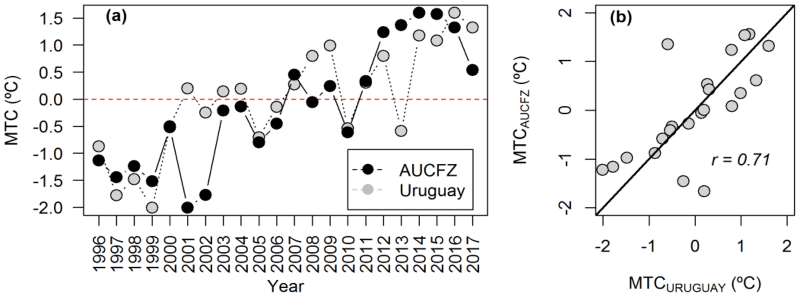

Fig. 6. (a) Mean temperature of the catch (MTC) anomaly for the Argentinean-Uruguayan Common Fishing Zone (ºC; black dots) and Uruguay (ºC; grey dots) based on CTMFM landings data. (b) Correlation between both time series shown in (a).

Table 1. MTC variants used in the study. Differences rely on different landing databases used for MTC calculation, the timeframe, the taxonomic resolution and the countries involved. CTMFM: Joint Technical Commission of the Uruguayan-Argentinean Maritime Front (CTMFM for its acronym in Spanish), AUCFZ: Argentinean-Uruguayan Common Fishing Zone.

MTC variants	Landings database used	Timeframe	Species considered
MTC	Gianelli & Defeo (2017)	1973-2017	21
MTC excluding main species	Gianelli & Defeo (2017)	1973-2017	19
MTC_{AUCFZ} (Uruguay and Argentina)	CTMFM	1996-2017	28

Table 2. Results of linear models between MTC and environmental predictors, without and with time-lag (up to three years). For all models, the Simpson Index (z-score) for fishing fleet diversity was considered without time lag. S.E.: standard error. RdlP: Río de la Plata.

	No time-lag		1-year time-lag		2-year time-lag		3-year time-lag	
Variable	Estimate	S.E.	Estimate	S.E.	Estimate	S.E.	Estimate	S.E.
z-score SSTA	0.40**	0.14	0.25	0.15	0.43**	0.14	0.47**	0.15
z-score Simpson Index	-0.46**	0.11	-0.55***	0.14	-0.46**	0.13	-0.52***	0.13
z-score RdlP discharge	-0.19	0.09	-0.23*	0.109	-0.16	0.11	-0.08	0.11
Intercept	0.00	0.09	-0.01	0.101	0.02	0.10	0.060	0.11
	R^2: 0.66		R^2: 0.61		R^2: 0.65		R^2: 0.64	

Table 3. Linear model relating the Mean Temperature of the Catch (MTC) with the sea surface temperature anomaly (SSTA) and the fishing fleet diversity (Simpson Index). S.E.: standard error. Significance levels: ***<0.001; **<0.01; *<0.05.

Variable	Estimate	S.E.	IC95%	p-value
z-score SSTA	0.43	0.14	[0.14-0.72]	0.0043**
z-score Simpson Index	-0.44	0.14	[-0.72-0.15]	0.0040**
Intercept	0	0.10	[-0.19-0.19]	