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The Influence of environmental factors on small pelagic target species (Sardine, Anchovy, and Mackerel) in the southern Alboran Sea (Western Mediterranean)

PhD Thesis

(Cotutelle and compendium)

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DECLARACIÓN DE AUTORÍA Y ORIGINALIDAD DE LA TESIS PRESENTADA PARA OBTENER EL TÍTULO DE DOCTOR

D./Dña AYMAN JGHAB
Estudiante del programa de doctorado DIVERSIDAD BIOLÓGICA Y MEDIO AMBIENTE de la Universidad de Málaga, autor/a de la tesis, presentada para la obtención del título de doctor por la Universidad de Málaga, titulada: THE INFLUENCE OF ENVIRONMENTAL FACTORS ON SMALL PELAGIC TARGET SPECIES (SARDINE, ANCHOVY AND MACKEREL) IN THE SOUTHERN ALBORAN SEA (WESTERN MEDITERRANEAN)

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The codirectors: Dr. Andreas REUL, Profesor Titular del Departamento de Ecología y Geología de la Universidad de Málaga Dr. Manuel VARGAS YÁÑEZ Científico Titular de OPIS del instituto español de Oceanografía (IEO-CSIC), Centro de Fuengirola.

CERTIFY THAT: Sr. Ayman JGHAB doctorate student of the Doctorate Programme, Biological Diversity and Environment, has realized at the University of Málaga, the Spanish Oceanographic Institute and University of Abdelmalek Essaadi, the investigation necessary for the redaction of the PhD thesis *"The influence of environmental factors on small pelagic target species (Sardine Anchovy, and Mackerel) in the southern Alboran Sea (Western Mediterranean)"* in cotutelle regime.

As extractive fishery is managed through international agreement based on scientific and socio-economic criteria, the subject of investigation is of international interest. The compendium format assures a wide and international readership of the main results of the Thesis, which provides an additional diffusion of the results apart of the diffusion by the Repository of the University of Málaga (RIUMA) and TESEO. Therefore, the directors confirm that the presented PhD. **Thesis is suitable for presentation in compendium format.**

As directors of the Thesis we authorize the defence of the Thesis in order to achieve the Doctorate degree in cotutelle regime and consider that the three publications:

(i) A. Jghab, M. Vargas-Yañez, A. Reul, M.C. Garcia-Martínez, M. Hidalgo, F. Moya, M. Bernal, M. Ben Omar, S. Benchoucha, A. Lamta. 2019. The influence of environmental factors and hydrodynamics on sardine (Sardina pilchardus, Walbaum 1792) abundance in the southern Alboran Sea, Journal of Marine Systems, Volume 191,Pages 51-63,https://doi.org/10.1016/j.jmarsys.2018.12.002.
(ii) A. Jghab, B. El Moumni, A. Reul, M. Vargas-Yáñez, M.C. García-Martínez, J. Chioua, F. Moya, S. El Arraf, M. Muñoz. 2023. Relationship between environmental factors changes and anchovy landing (Engraulis encrasicolus) in the south Alboran Sea. Egyptian Journal of Aquatic Biology & Fisheries 2023, doi: In press.
(iii) A. Ayman1, A. Reul, M. Vargas Yáñez, B. El Moumni, M.C. Garcia-Martínez, M. Muñoz, F. Moya, S. El Arraf. 2013. Environmental factors changes and its association with the catches fluctuations of Atlantic chub mackerel (Scomber Colias, Gmelin, 1789) in the south Alboran Sea (Western Mediterranean Sea). Egyptian Journal of Aquatic Biology & Fisheries, 2023. Doi: In press

endorse the **sufficient quality to the PhD thesis for the defence of the Thesis in cotutelle and compendium format.** Furthermore, we guarantee that none of the three mentioned articles above have been used by any of the coauthors in previous PhD Thesis.

And for the record, in compliance with current provisions, we sign this accreditation, on June 21, 2023.

Dr. Andreas REUL Dr. Manuel VARGAS YÁÑEZ

Summary

Abstract

Climate change is projected to shift most terrestrial and marine species communities to the poles. This is because temperature is a key factor in the distribution of marine animals due to direct (e.g. metabolism, especially tolerance to planktonic larval stages) and indirect effects (e.g. substitution of other environmental conditions, predator-prey distribution) tolerance, (especially at the planktonic larval stage) manifested as latitudinal changes or habitat expansion/contraction, especially for mobile species such as fish. For example, benthic species have their average latitude, depth, or both shifted). Over a 25-year period, in response to the recent enlargement of the North Sea margin, the frontier moved northward with warming, but differences in movement speed between species caused migratory species to move faster and have smaller life cycles. (Southward et al., 1995; Parmesan and Yohe, 2003; Beaugrand and Ibáñez, 2004).

For instance, climate change may also alter plankton and fish community structures. In fact, Boyd and Doney (2002) conclude that regional shifts are as important as changes in large-scale productivity. Seasonal shifts in biomass and dominant phytoplankton in the subarctic-subtropical transition were realted to global warming across all regions. These changes in phytoplankton may provide further or additional explanations for large-scale changes in zooplankton biogeography in many places in response to changes in climatic zones (Beaugrand et al., 2002).

For example, the Bering Sea has shown relevant changes since around 1990, leading to speculation as to whether the increase in jellyfish biomass was a result of human disturbance. However, peak levels of gelatinous zooplankton in the Bering Sea have declined significantly and have remained low since 2000 (King. 2005), so it is still unclear whether the blooms in the 1990s were related to long-term trends or isolated events. In the Bay of Biscay, many fish species live on the southern or northern boundaries of their ranges, and recent climate change has altered the structure of fish communities. In the negative trend group, one-third (seven) of the species were characterized by a northern distribution and a narrow latitudinal distribution. Another group of biomass consists mainly of transitional species with no long-term trend.

All in all, many fish species are found at the southern or northern limits of their range, and recent climate change has resulted in changes in the fish community structure in this bay (Poulard and Blanchard, 2005).

The impact of further warming on commercial fisheries of cod, flounder, blue whiting or redfish is through continued distributional changes as well as changes in food webs. For example, different displacement rates may lead to changes in the spatial overlap between species, especially disrupting interactions. GLOBEC studies from 2003 to 2005 reported a sudden increase in warm-water sardine pelagic species (Pilchardus) in the northwestern North Sea, suggesting that anchovies and sardines are now spawning in the southern North Sea. This increase would have more to do with the recovery of sardine populations near California than with allowing sardines to migrate to the North Sea related to the warmer waters (Voss et al. 2009). An example of a direct effect of temperature on recruitment is given by Planque and Frédou (1999), who studied cod recruitment in different regions of the ocean. In regions where temperatures are below optimum for cod, Drinkwater (2005) used predicted changes in the temperature field and known observed cod responses to temperature changes to estimate the response of North Atlantic cod stocks.

It is thought that some oceans could disappear by 2100 due to projected temperature changes, with areas of the southern North Sea and George Shoal receding. According to Drinkwater (2005), the response to future climate change is highly uncertain and depends on changes in other climate and ocean variables besides temperature, such as growth inducted by "the optimal growth temperature" hypothesis to explain the climate change to some small pelagic species regime shift (ex: sardine and anchovy). They suggest that this variation is caused by differences in the optimum temperature for growth rate early in life, with anchovies having a higher temperature optimum (22 °C) than sardines (16 °C). Between optimal temperatures, there may be fluctuations in the growth rates of the two species, and changes in the species' occurrence in the western North Pacific. Regardless of the underlying processes, further climate change is expected to correspondingly amplify these geographic differences in recruitment, leading to shifts in species distribution especially for some vulnerable key species such as small pelagic species.

Small pelagic species are very important in commercial fisheries, making up 22% of global marine catches around the world (FAO, 2011). This is true for the Mediterranean and Black Sea where anchovies (393,500 tons/year) and sardines (186,100 tons/year) are the dominant species, accounting for 26% and 12% of the total catch (FAO, 2016). These species play a key role in marine ecosystems because of their high biomass and their role in linking lower and higher trophic levels (Bakun, 1996). Small pelagic fish with fast growth, early maturation, and few reproductive age classes are highly vulnerable to environmental changes due to their strong dependence on the sub-surface hydro-climatology and the spatial and temporal variability of primary production (Brosset et al., 2015, 2016, 2017; Hidalgo et al., 2011; Lloret et al., 2004).

Another factor affecting these species is the increasing fishing effort. Catches are experiencing negative trends suggesting a possible decline of the stocks (GFCM, 2016). Pinsky et al. (2011) demonstrated that the probability of these fisheries collapsing is similar to that observed for large body and late-maturity species. Climate change is recognized as another potential threat to exploited marine resources (FAO, 2008), with changes in sea temperature potentially altering the biology of marine species, their seasonal cycles, and their distribution.

These changes could have a higher impact on small-bodied and fast growing species, like small pelagic fish (Perry et al., 2005). Because of its reduced dimensions when compared with the world oceans, and its semi-enclosed character, the Mediterranean Sea could be particularly sensitive to climate change (Garcia- Martinez et al., 2018; Vargas-Yáñez et al., 2017; Bethoux et al., 1999).Tugores et al. (2011) showed the impact of environmental variables such as temperature, salinity, and chlorophyll concentration on sardine habitat suitability, and Raybaud et al. (2017) suggested that climate change could cause a moderate decrease in anchovy abundance during the 21st century. Brosset et al. (2017) found a decrease in anchovy and sardine body condition, but this could not be related to the main climatic indices. These authors suggested that regional environmental changes and their impact on phyto- and zooplanktonic assemblages could be linked to this body condition decrease through bottom-up control mechanisms (Brosset et al., 2015, 2016). Sabatés et al. (2006, 2009) showed that sea water warming was responsible for the change in the distribution of *Sardinella aurita* which had extended northwards into the North Western Mediterranean Sea (Catalan shelf).

As marine species are one the most impacted species by these environmental changes, we have to remember that these effects could have a significant impact of the economy of certain countries' economies relaying on fishing activities, such as Morocco. In fact, the Moroccan fishery catches more than 1.42 million tons of marine commercial species, and generates sales of more than 15 billion MAD, accounts for 2% of GDP, and employs approximately 360,000 people directly or indirectly (DPM, 2021). Historically, small pelagic species represent the bulk of Morocco's fisheries potential, accounting for 80% of fish production. Small pelagic resources mainly include clupeid species (*Sardina pilchardus*, *Sardinella aurita and Sardinella madarensis*), scombrids (*Scomber colias*), carangids (*Trachurus trachurus, Trachurus trecae and Trachurus mediterraneus*) and engraulids (*Engraulis encrasicolus*) (INRH, 201).

As fishing for small pelagic species is the main activity in the Mediterranean. This activity has decreased over the past two decades, leading to increased interactions between the top predators and seine vessels in the region. Bottlenose dolphin groups attacks fishing boats while circling pelagic fish such as sardines and anchovies, causing huge economic losses to fishermen and putting these protected species at high risk of injuries (Malouli et al., 2020).

While the decline in these small pelagic fisheries is thought to be primarily due to fishing, climate change and its impact on the disruption of the marine ecosystem may also have affected these species, especially since the Mediterranean Sea is a semi-enclosed and highly sensitive to environmental changes (Abdellaoui et al., 2017; MM Garcia et al., 2018).

In fact, the reasons for this decline have been largely debated by Moroccan fishermen, who claims that their activities are not the main cause of this decline, and that a great deal of research has been done on the evolution of these fish stocks, as well the fishing impacts (monitored annually by the INRH), but very few studies have attempted to understand the relationship between the dynamics of these species and changing oceanographic conditions in the region (Abdellaoui et al., 2017; Jghab et al., 2019; Vargas et al. et al., 2020; INRH, 2016).

In our study data on the monthly main small pelagic landings (Sardine, Anchovy, and Mackerel) on the Mediterranean Moroccan coast from 1983 to 2020 were obtained from the Moroccan National Office of Fisheries For the main small pelagic fishing ports, Mdiq, Hoceima, Nador, and Ras Kebdana, although some other, smaller ports also contribute to the total sardine landings in this area (less than 1 %).

The fleet effort (fishing days) was only available from 2009 to 2020. Landings per Unit Effort (LPUE) for this period were estimated as landings in metric tons divided by the number of fishing days.

In addition to small pelagic landings, information on environmental variables that potentially impact sardine recruitment and abundance were obtained from various sources. These variables are sea surface temperature (SST), sea surface salinity (SSS), surface chlorophyll-a concentration (Chl-a), the west-east (u) and south-north (v) components of the wind, the North Atlantic Oscillation (NAO) index, the Mediterranean Oscillation Index (MOI), and the Western Mediterranean Oscillation index (WeMO). SST, SSS, and Chl-a data were averaged over the southern part of the Alboran Sea, from 5.5°W to 2°W and from 35°N to 36°N.

Daily sea surface temperature data from 1981 to 2020 were obtained from NOAA high-resolution SST data, from the NOAA/OAR/ ESRL PSD, Boulder, Colorado, USA web site at https://www.esrl.noaa. gov/psd/ (Reynolds et al., 2007). This data set has a 0.25° × 0.25° resolution. Daily salinity data from 1987 to 2020 were obtained from The Copernicus Marine Environment Monitoring Service (Simoncelli et al., 2014). This dataset has a 0.063° × 0.063° resolution. Daily Chlorophyll- A data were also obtained from the Copernicus website. These data have a spatial resolution of 1 km × 1 km and run from 1997 to 2020 (available from GOS-ISAC-CNR, Volpe et al., 2012). Daily wind data with a 2.5° × 2.5° resolution (u, west-east and v, south-north components) were obtained from NCEP Reanalysis, from the NOAA/OAR/ ESRL PSD, Boulder, Colorado, USA web site at https://www.esrl.noaa. gov/psd/ (Kalnay et al., 1996).

The AJ in the Gibraltar Strait was considered to be another environmental variable with the potential to impact small pelagic fish. However, long time series for this variable are not available. To circumvent this limitation, and according to García-Lafuente et al. (1998) and Vargas-Yáñez et al. (2002), the AJ can be considered to be in geostrophic equilibrium with the cross-strait sea level difference. According to this expression, the Algeciras-Ceuta sea level difference can be considered a good indicator of the changes in the inflowing velocity. Monthly sea level time series for Algeciras and Ceuta were obtained from the tide gauge network of the Instituto Español de Oceanografía and Permanent Service for Mean Sea Level (www.psmsl.org). Monthly time series for the cross-strait sea level difference were constructed for 1981 to 2020.

Finally, the main atmospheric circulation patterns in the North Atlantic and Mediterranean Sea can influence the productivity of Mediterranean waters, in addition to the distribution and abundance of plankton (García-Comas et al., 2011; Fernández de Puelles et al., 2007) and high trophic level organisms (Hidalgo et al., 2011, 2015). Winter (December to March) and annual NAO indices were obtained from the National Centre for Atmospheric Research (2017). The NAO index is defined as the normalized sea level pressure difference between the Azores and Iceland. The Mediterranean Oscillation Index (MOI) is defined as the normalized sea level pressure difference between Gibraltar and Israel. MOI values were obtained from the Climate Research Unit, University of East Anglia. The Western Mediterranean Oscillation index is more local, and defined as the pressure difference between San Fernando, in the Gulf of Cádiz, Spain, and Padua, in northern Italy (Martín-Bide and López-Bustins, 2006). These data were obtained from the Climatology Group at Barcelona University (www.ub.edu/gc/en).

Monthly landings from the Mdiq, Hoceima, Nador, and Ras Kebdana ports were aggregated. The high variability in monthly time series of sardine landings is beyond the scope of this current study. Therefore, the monthly time series were annually averaged, in other words, the twelve-monthly values for each year were averaged. In this way, we obtained one data point per year. Many studies have shown that LPUE are an appropriate proxy for the abundance of different species. Ruiz et al. (2013) used LPUE to estimate the variability of anchovy abundance in the Alboran Sea, Thiaw et al. (2017) used LPUE as a proxy for the abundance of Sardinella along the northwestern African coast, and Massutí et al. (2008) and Hidalgo et al. (2011) used it to analyze European Hake in the Balearic Sea.

Nevertheless, fishing effort data for the fleet targeting sardine in Moroccan Alboran waters are only available from 2009 onwards. This considerably reduces the length of the time series analyzed and the possibility of finding meaningful relationships with environmental variables. Using landings instead of LPUE would increase the length of the available time series, but changes in sardine landings could simply be the result of changes in the fishing effort, and not be a reflection of the real variability in the stock abundance. To check this possibility, a regression analysis between landings and LPUE was undertaken for both the annual and monthly time series, which revealed a high and significant correlation in both cases, supporting the use of landings as a response variable.

This result indicates that the abundance variability of small pelagic fish in the southern Alboran Sea could be described through landing data. This result coincides with the high level of correlation between landings and LPUE for the northern sector of the Alboran Sea. This close relationship between landings and LPUE has already been demonstrated for the juvenile sardine landings in Vigo (Atlantic Iberian coast, Guisande et al., 2004) and the port of Tarragona (northwestern Mediterranean, Lloret et al., 2004).

For the environmental data, SST, SSS, and surface Chl-a were processed in two different ways. The data were distributed on regular grids at different resolutions. In order to describe the fluctuations in the variables directly affecting the southern Alboran Sea, grid points from 5.5° W to 2° W and to the south of 36° N were selected and annually averaged. In this way, annual time series for SST, SSS, and Chl-a were obtained for the southern half of the Alboran Sea.

Directly calculating the mean values for the southern Alboran Sea allows us to analyze the relationships between the sardine landings from this sector and the environmental variables observed in the same geographical area. Nevertheless, the Alboran Sea has highly energetic hydrodynamics. Primary production, or the phyto- and zooplankton distributions, which can affect the fish stocks in certain regions (Brosset et al., 2015, 2016, 2017) could result from advection and other processes occurring in nearby locations. A time series of SST, SSS, and Chl-a is available for each grid point (latitude/longitude) within the selected geographical area (Alboran Sea). These time series are not statistically independent, and the variability at each grid point can be considered to be the result of variation in several spatial structures. Each of these spatial structures is an EOF.

Linear trends were estimated by fitting a straight line to all the time series (sardine landings and environmental predictors) by means of least square fit. The slope represents the mean annual rate of change. Confidence intervals at the 95% confidence level were obtained for the slope considering a Student's t-distribution after checking for the normality of the residuals (Kolmogorov-Smirnov tests, see Zar, 1984 for instance). All the calculations involved in the model selection were repeated using both original and detrended time series. Although all the environmental variables described above are based on sound scientific knowledge, the number of predictors used to model the variability of sardine landings should be kept as low as possible, according to the degrees of freedom in the analysis (Burnham and Anderson, 2002). For this reason, a first exploratory analysis of the data was undertaken. Scatter plots of SST, SSS, Chl-a, SLD, and climatic in- dices (NAO, MOI, WeMO) versus sardine landings were analyzed.

The same analysis was carried out for the main variability modes of SST, SSS and Chl-a. Sardine landings were regressed on these variables, and only those significantly correlating at the 0.1 significance level were considered potential predictors for the generation of candidate linear models. Those variables not significantly correlating were discarded. This analysis was considered for the environmental variables already described, with and without a one-year time lag.

In this first analysis, the complete time series were used, that is, no trend was subtracted from either the sardine landings, or the predictor variables. The procedure for selecting the best approximating model was the following (Vargas-Yáñez et al. 2009): one year of the time series (both response and predictors) was suppressed. A multiple linear regression was applied to the remaining n-1 data. A forward stepwise procedure was used and partial F values were calculated for each predictor at each step. A probability of $p = 0.05$ was used to enter a new predictor into the model, and $p = 0.1$ to remove it (see, for instance, Draper and Smith, 1981). Co-linearity between predictors was checked by means of the Variance Inflation Factor (VIF), which was below 3 for all the predictors and models considered. This procedure was repeated n times (each time different data was suppressed from the original time series). For each step, a different model was selected for the forward stepwise regression and this was considered a candidate model.

Finally, once a set of candidate models had been selected, a multiple linear regression was applied to each candidate model and for the complete time series (n data). The AICc (Corrected Akaike Information Criteria) were calculated according to Burnham and Anderson (2002). Finally, the candidate model with the minimum AICc was selected as the best approximating model. Figure S1 in the supplementary material is a conceptual diagram explaining the procedure used for the model selection.

Once the final model had been selected, a cross-validation procedure was applied (Francis 2006; Lavín et al. 2007; Vargas-Yáñez et al. 2009). Using the selected model, landings for each year in the time series were estimated using the remaining n-1 data, and the prediction was tested against the default estimate, which was considered to be the mean value of the time series (using the n-1 data for the estimation). In order to analyze the relationship between sardine landings and environmental variables only on an inter-annual time scale, the sardine landings and potential predictors (with and without time lag) were de-trended.

For instance, sardine landings were considered as a linear trend, representing long-term changes, plus a term representing the inter-annual variability.

The results of the modeling was quite different for each specie, for instance if the trends are not removed from the sardine landing and environmental time series, the best-chosen linear model relates sardine landing to the previous year's SST, fourth salinity pattern (from Principal Component Analysis), and SLD in the same year as landing (with no time delay). It is also worth emphasizing that there is a negative relationship between landings and SST. One might argue that positive warming trends are partly responsible for the downward trend in sardine landings. The relationship between landings and SLD could indicate that a negative trend in SLD induces a negative trend in sardine landings. The possibility of a correlation between the small pelagic fish and the kinetic energy of the inflowing AJ is not a new hypothesis. AJ with high kinetic energy would increase primary production in the northern Alberland Sea, but also increases larval dispersion, which would negatively affect larval survival and annual anchovy recruitment. In the southern Alboran Sea, there was a positive relationship between AJ velocity and sardine abundance, with higher velocity associated with higher abundance and vice versa. Finally, a fourth salinity pattern was negatively associated with sardine landings. However, this association can only be related to inter-annual variability. This pattern of change did not show a significant overall trend, despite a positive trend in mean salinity across the region. In addition to the possible effects of long-term temperature and SLD changes on the decline in sardine landings, the chosen linear model was able to reproduce the long-term and inter-annual variations in sardine landings and explained 64% of the variance of the observations.

A second possibility considered in this work is to remove the linear trend from the response and predictor variables. In this approach, a linear trend is determined by fitting a straight line to the landing time series, and the residuals represent annual changes around the linear behavior. This approach cannot explain the long-term decline in sardine landings, and the model assesses the impact of annual fluctuations in environmental variables. Two possible models were obtained:

One model positively correlated landing residuals with Chl-a concentrations with a time lag of one year (coefficient 1838 t mg Chl-a^{-1} m^{-3}) and with SLD (coefficient 8 t mm^{-1}). In this model, there is also a positive correlation between landing, chlorophyll and SLD and the first model.

Thus, the results of these two models suggest that increased Chl-a concentrations in the year preceding or during the year when sardine catches were recorded positively affected sardine abundance. Also, the kinetic energy of the incoming AJ seems to be an important factor. In all the cases, very similar results were obtained, with an increase/decrease of about eight tons for every 1 mm increase/decrease of SLD across the strait. When the time series of sardine landings were reconstructed using the estimated linear trend and the linear model of the residuals or de-trended.

In addition to long-term and inter-annual variations in sardine landings, seasonal variations were also evidenced by average landings for each month of the year calculated using the entire time series. This seasonal cycle shows minimum landings from February to April period. The average Sea surface temperature for these months was also calculated from the satellite data used in this study; these values are between 15.5 °C and 16.5 °C. Landing maxima were recorded from October to January, showing a clear recurring pattern of maximum landings in autumn, which likely reflects sardine replenishment that is completed each September. As the breeding season for sardines is between January and March it can be assumed that the minimum landings correspond to the spawning season.

From the available data it can be suggested that the breeding season in the southern Alboran Sea is delayed compared to the nearby Atlantic coast and the northern Alboran Sea, or simply that the minimum landings correspond to a few days after spawning. As the recruitment season (with much higher probability of catches) will happen in the following next months.

For anchovy, using trended time series, environmental factors explained 60% to 79% of the total variance in anchovy landings, and most of the resulting models were statistically significant. Temperature, salinity, and the U wind component all displayed a negative association with anchovy landings. On the other hand, the Atlantic Jets' velocity as it travels through the Strait of Gibraltar was positively correlated with anchovy landings.

Unfortunately, since most environmental factors and anchovy landings in the Mediterranean have shown clear trends, which may underscore the correlations observed in our model. Using trend-adjusted time series, no association between anchovy frequency and environmental variables was found.

Therefore, while SST, SSS, U, and V can be used to predict anchovy abundance along seasonal cycles, they cannot predict long-term trends. This may be due to two factors: the environmental data show no significant trend over the period analyzed (38 years), and there are other, more important factors affecting the decline in anchovy abundance in the southern Alboran Sea, such as the increased fishing pressure on the most important targeted species.

For the case of mackerel, upon using original data, sea surface salinity was selected for all models, accordingly this factor is the most important driver of Atlantic mackerel in this region. In fact, SSS remains the most important predictor after using the de-trended time series. There was a positive correlation with mackerel landings, suggesting that this species prefers higher salinity, and that recent salinity increases in the region had a positive impact on this species. Mackerel's physiological adaptations to endure salinity variations are probably what contribute to the SSS's beneficial effects on it. In particular, A. mackerel can control its bodily fluids to maintain osmotic balance in varying salinities and has a high tolerance for saltwater. As a result, raising SSS may be advantageous for this specie population. As a matter of facts, salinity doesn’t impact this specie but it does highlight a more complex water fertilization process, as it was linked with more rich nutrient water mass entering the Bay of Biscay. For instance, a salinity increase in our study region could indicate a higher intensity of upwelling in the Alboran Sea.

The second most common predictor in the models was anchovy landings. For some reason, this other small pelagic species was positively correlated with mackerel in both the original time series and the de-trended time series. This positive association was not observed as sardine catch was not selected in any significant model. According to the results of our study, anchovy catch also served as a significant predictor. This conclusion can be explained by the possibility that these two species coexist in the same habitat or by the close relationship between their respective catch rates. As these two species do not compete for prey, and chub mackerel could feed on this specie.

Over and above that, several studies have reported a positive relationship between anchovy and mackerel abundance, indicating that these two species co-occur and share similar ecological niches in the marine ecosystem.

Moreover, mackerel are known to prey on anchovy, but also the feeding range of Atlantic chub mackerel includes fish from three ecological groups, Juveniles of mass epipelagic species such round sardinella, Cunene horse mackerel, European anchovy, and European pilchard were included in the first category. Mesopelagic species from the Paralepididae and Myctophidae families made up the second group. Benthic and bottom species are the third group. Crustaceans and zooplankton have been the secondary food sources for the Atlantic Chub. The distribution and abundance of Atlantic mackerel and its prey can be influenced by a wide range of environmental conditions. As important target species it is important to understand the physical and trophic interactions that triggers its abundance and how A. mackerel abundance might be affected by different climate change scenarios.

SLD, which represents the nutrient and Chl-a rich Atlantic current from the Strait of Gibraltar, appears to be another limiting factor for mackerel, as higher levels lead to more nutrient-rich Atlantic current entering the Alboran Sea. This could be explained by the fertilization effect of AJ. The Atlantic jets flowing into the region have a substantial impact on animals residing in the Aboran Sea, especially small pelagic fish species. These jets draw water from the Atlantic that is fertilized because of mixing processes within the Strait of Gibraltar increase primary production and, in turn, the number of small pelagic fish.

Sea surface temperature is the fourth environmental parameter selected. It was selected using only the full time series, not the de-trended dataset. This factor also showed a positive association with species, but was ignored due to the de-trended data, suggesting that the effect of this factor on the species only occurred on an inter-annual (seasonal) scale. Mackerel abundance and dispersion may benefit from rising temperatures. The ecological temperature range of Mackerel tends to move more northward as temperatures rise, presenting the species with better climatic conditions. The ocean warming brought on by climate change may result in a possible rise of A. mackerel. This is true in our case as the increase of increase of the sea surface temperature showed a positive relationship with increase of landing for this specie.

On the other hand, Chl-a and V wind were selected using only the de-trended time series and show two opposite effects. Positive correlations were observed in mackerel with V wind, which may indicate that northerly winds have a positive effect on mackerel abundance. Hence, the wind speed and direction can also have a considerable impact on small pelagic species.

Changes in wind speed may affect ocean currents, which may alter the distribution of food resources and the movement of larvae and eggs. For instance, increasing wind speed can increase water column mixing, which reduces phytoplankton concentrations and the amount of food that Mackerel specie has access to. According to our findings, there is a surprising negative association between the ambient components Chl-a (primary production indicator) and the specie landing. This component has a negative correlation coefficient and was only included twice in the models.

In short, we can see how it is challenging to model the reaction of these small pelagic species to environmental changes. As it also very difficult to accurately predict how climate change will affect small pelagic species due to the lack of established long-term monitoring plans, scarcity of data, complex environmental changes, and overfishing.

This is why is it so important to conduct further interdisciplinary study to try to fully understand how the environmental change, and fishing impact the ecosystem functioning in general, and on small pelagic species dynamic and population in particular.

Resumen

Se prevé que el cambio climático desplazará a la mayoría de las comunidades de especies terrestres y marinas a los polos. Esto se debe a que la temperatura es un factor clave en la distribución de los animales marinos debido a los efectos directos (por ejemplo, el metabolismo, especialmente la tolerancia a los estadios larvarios planctónicos) e indirectos (por ejemplo, la sustitución de otras condiciones ambientales, la distribución entre depredadores y presas) (especialmente en la fase larvaria planctónica) que se manifiestan en forma de cambios de latitud o de expansión/contracción del hábitat, especialmente en especies móviles como los peces. Por ejemplo, las especies bentónicas tienen su latitud promedio, su profundidad o ambas desplazadas). Durante un período de 25 años, en respuesta a la reciente ampliación de la margen del Mar del Norte, la frontera se desplazó hacia el norte debido al calentamiento, pero las diferencias en la velocidad de movimiento entre las especies hicieron que las especies migratorias se movieran más rápido y tuvieran ciclos de vida más cortos. (Southward et al., 1995; Parmesan y Yohe, 2003; Beaugrand e Ibáñez, 2004).

Por ejemplo, el cambio climático también puede alterar las estructuras de las comunidades de peces y plancton. De hecho, Boyd y Doney (2002) concluyen que los cambios regionales son tan importantes como los cambios en la productividad a gran escala. Los cambios estacionales en la biomasa y el fitoplancton dominante en la transición subtropical subártica estuvieron relacionados con el calentamiento global en todas las regiones. Estos cambios en el fitoplancton pueden proporcionar explicaciones adicionales o adicionales de los cambios a gran escala en la biogeografía del zooplancton en muchos lugares en respuesta a los cambios en las zonas climáticas (Beaugrand et al., 2002).

Por ejemplo, el mar de Bering ha registrado cambios importantes desde alrededor de 1990, lo que ha llevado a especular sobre si el aumento de la biomasa de medusas se debió a perturbaciones humanas. Sin embargo, los niveles máximos de zooplancton gelatinoso en el mar de Bering han disminuido significativamente y se han mantenido bajos desde el año 2000 (King. 2005), por lo que aún no está claro si las floraciones de la década de 1990 estuvieron relacionadas con tendencias a largo plazo o con eventos aislados. En el Golfo de Vizcaya, muchas especies de peces viven en los límites sur o norte de sus áreas de distribución, y el cambio climático reciente ha alterado la estructura de las comunidades de peces. En el grupo de tendencia negativa, un tercio (siete) de las especies se caracterizó por una distribución septentrional y una distribución latitudinal estrecha.

Otro grupo de biomasa consiste principalmente en especies en transición sin tendencias a largo plazo. En general, muchas especies de peces se encuentran en los límites sur o norte de su área de distribución, y el cambio climático reciente ha provocado cambios en la estructura de la comunidad de peces de esta bahía (Poulard y Blanchard, 2005).

El impacto de un mayor calentamiento en las pesquerías comerciales de bacalao, platija, bacaladilla o gallineta nórdica se debe a los continuos cambios en la distribución, así como a los cambios en las redes tróficas. Por ejemplo, las diferentes tasas de desplazamiento pueden provocar cambios en la superposición espacial entre especies, interrumpiendo especialmente las interacciones.

Los estudios de GLOBEC realizados entre 2003 y 2005 informaron de un aumento repentino de las especies pelágicas de sardinas de aguas cálidas (Pilchardus) en el noroeste del Mar del Norte, lo que sugiere que las anchoas y las sardinas ahora están desovando en el sur del Mar del Norte. Este aumento tendría más que ver con la recuperación de las poblaciones de sardinas cerca de California que con permitir que las sardinas migren al Mar del Norte debido a las aguas más cálidas (Voss et al., 2009). Planque y Frédou (1999) ofrecen un ejemplo de un efecto directo de la temperatura en el reclutamiento, quienes estudiaron el reclutamiento de bacalao en diferentes regiones del océano. En las regiones donde las temperaturas están por debajo de las óptimas para el bacalao, Drinkwater (2005) utilizó los cambios previstos en el campo de temperatura y las respuestas observadas conocidas del bacalao a los cambios de temperatura para estimar la respuesta de las poblaciones de bacalao del Atlántico Norte. Se cree que algunos océanos podrían desaparecer para el 2100 debido a los cambios de temperatura proyectados, con el retroceso de áreas del sur del Mar del Norte y George Shoal. Según Drinkwater (2005), la respuesta al cambio climático futuro es muy incierta y depende de los cambios en otras variables climáticas y oceánicas además de la temperatura, como el crecimiento inducido por la hipótesis de «la temperatura de crecimiento óptima» para explicar el cambio climático a un cambio de régimen en algunas pequeñas especies pelágicas (por ejemplo, la sardina y la anchoa). Sugieren que esta variación se debe a las diferencias en la temperatura óptima para la tasa de crecimiento en las primeras etapas de la vida, ya que las anchoas tienen una temperatura óptima más alta (22 °C) que las sardinas (16 °C). Entre las temperaturas óptimas, puede haber fluctuaciones en las tasas de crecimiento de las dos especies y cambios en la presencia de las especies en el Pacífico Norte occidental. Independientemente de los procesos subyacentes, se espera que el cambio climático amplifique en consecuencia estas diferencias geográficas en el reclutamiento, lo que provocará cambios en la distribución de las especies, especialmente en el caso de algunas especies clave vulnerables, como las pequeñas especies pelágicas.

Las pequeñas especies pelágicas son muy importantes en la pesca comercial, ya que representan el 22% de las capturas marinas mundiales en todo el mundo (FAO, 2011). Este es el caso del Mediterráneo y el Mar Negro, donde las anchoas (393.500 toneladas al año) y las sardinas (186.100 toneladas al año) son las especies dominantes y representan el 26% y el 12% de la captura total (FAO, 2016). Estas especies desempeñan un papel clave en los ecosistemas marinos debido a su alta biomasa y a su papel en la vinculación de los niveles tróficos inferiores y superiores (Bakun, 1996).

Los peces pelágicos pequeños con un crecimiento rápido, una maduración temprana y pocas clases en edad reproductiva son muy vulnerables a los cambios ambientales debido a su fuerte dependencia de la hidroclimatología del subsuelo y de la variabilidad espacial y temporal de la producción primaria (Brosset et al., 2015, 2016, 2017; Hidalgo et al., 2011; Lloret et al., 2004).

Otro factor que afecta a estas especies es el aumento del esfuerzo pesquero. Las capturas están experimentando tendencias negativas, lo que sugiere una posible disminución de las poblaciones (GFCM, 2016). Pinsky et al. (2011) demostraron que la probabilidad de que estas pesquerías colapsen es similar a la observada en las especies de cuerpos grandes y de madurez tardía. Se reconoce que el cambio climático es otra amenaza potencial para los recursos marinos explotados (FAO, 2008), ya que los cambios en la temperatura del mar podrían alterar la biología de las especies marinas, sus ciclos estacionales y su distribución.

Estos cambios podrían tener un mayor impacto en las especies de cuerpo pequeño y crecimiento rápido, como los peces pelágicos pequeños (Perry et al., 2005). Debido a sus dimensiones reducidas en comparación con los océanos del mundo y a su carácter semicerrado, el mar Mediterráneo podría ser particularmente sensible al cambio climático (Garcia-Martinez et al., 2018; Vargas-Yáñez et al., 2017; Bethoux et al., 1999). Tugores et al. (2011) mostraron el impacto de variables ambientales como la temperatura, la salinidad y la concentración de clorofila en la idoneidad del hábitat de las sardinas, y Raybaud et al. (2017) sugirieron que el cambio climático podría provocar una disminución moderada de la abundancia de anchoas durante el siglo XXI. Brosset et al. (2017) encontraron una disminución en el estado corporal de la anchoa y la sardina, pero esto no pudo relacionarse con los principales índices climáticos. Estos autores sugirieron que los cambios ambientales regionales y su impacto en los conjuntos fitoplanctónicos y zooplanctónicos podrían estar relacionados con esta disminución de la afección corporal mediante mecanismos de control de abajo hacia arriba (Brosset et al., 2015, 2016). Sabatés et al. (2006, 2009) demostraron que el calentamiento del agua del mar era responsable del cambio en la distribución de la Sardinella aurita, que se había extendido hacia el norte hasta el noroeste del mar Mediterráneo (plataforma catalana).

Dado que las especies marinas son una de las especies más afectadas por estos cambios ambientales, debemos recordar que estos efectos podrían tener un impacto significativo en la economía de las economías de ciertos países que dependen de las actividades pesqueras, como Marruecos.

De hecho, la pesquería marroquí captura más de 1,42 millones de toneladas de especies marinas comerciales y genera ventas de más de 15 000 millones de dinares marroquíes, representa el 2% del PIB y emplea a aproximadamente 360 000 personas de forma directa o indirecta (DPM, 2021). Históricamente, las pequeñas especies pelágicas representan la mayor parte del potencial pesquero de Marruecos y representan el 80% de la producción pesquera. Los recursos pelágicos pequeños incluyen principalmente especies de clupeides *(Sardina pilchardus, Sardinella aurita y Sardinella madarensis*), escómbridos (*Scomber colias*), carángidos (Trachurus trachurus, Trachurus trecae y Trachurus mediterraneus) y engraulidos (*Engraulis encrasicolus*) (INRH, 201).

Ya que la pesca de pequeñas especies pelágicas es la actividad principal en el Mediterráneo. Esta actividad ha aumentado en las últimas dos décadas, lo que ha provocado un aumento de las interacciones entre los principales depredadores y los barcos de cerco de la región. Los grupos de delfines mulares atacan a los barcos de pesca mientras rodean peces pelágicos como las sardinas y las anchoas, lo que provoca enormes pérdidas económicas a los pescadores y pone a estas especies protegidas en alto riesgo de sufrir lesiones (Malouli et al., 2020).

Si bien se cree que la disminución de esta pequeña pesquería pelágica se debe principalmente a la pesca, el cambio climático y su impacto en la alteración del ecosistema marino también pueden haber afectado a estas especies, especialmente dado que el mar Mediterráneo es un mar semicerrado y muy sensible a los cambios ambientales (Abdellaoui et al., 2017; MM Garcia et al., 2018). De hecho, los pescadores marroquíes han debatido ampliamente las razones de esta disminución, quienes afirman que sus actividades no son la causa principal de esta disminución y que se han realizado muchas investigaciones sobre la evolución de estas poblaciones de peces, así como sobre los impactos de la pesca (monitoreados anualmente por el INRH), pero muy pocos estudios han intentado entender la relación entre la dinámica de estas especies y las condiciones oceanográficas cambiantes en la región (Abdellaoui et otros, 2017; Jghab y otros, 2019; Vargas y otros, 2020; INRH, 2016).

En nuestro estudio, los datos sobre los principales desembarques de pequeños pelágicos mensuales (sardina, anchoa y caballa) en la costa mediterránea marroquí entre 1983 y 2020 se obtuvieron de la Oficina Nacional de Pesca de Marruecos.

Para los principales pequeños puertos pesqueros pelágicos, Mdiq, Hoceima, Nador y Ras Kebdana, algunos otros puertos más pequeños también contribuyen al total de desembarques de sardinas en esta zona (menos del 1%). El puerto de la flota (días de pesca) solo estuvo disponible de 2009 a 2020. Los desembarques por unidad de Effort (LPUE) para este período se estimaron dividiendo los desembarques en toneladas métricas por el número de días de pesca.

Además de los pequeños desembarques pelágicos, se obtuvo información sobre las variables ambientales que podrían afectar el reclutamiento y la abundancia de sardinas de diversas fuentes. Estas variables son la temperatura de la superficie del mar (SST), la salinidad de la superficie del mar (SSS), la concentración de clorofila a en la superficie (CHL-a), los componentes oeste-este (u) y sur-norte (v) del viento, el índice de oscilación del Atlántico Norte (NAO), el índice de oscilación del Mediterráneo (MOI) y el índice de oscilación del Mediterráneo occidental (WeMO). Los datos de SST, SSS y CHL-a se promediaron en la parte sur del mar de Alborán, de 5,5° O a 2° O y de 35° N a 36° N.

Los datos diarios de temperatura de la superficie del mar de 1981 a 2020 se obtuvieron de datos SSTdata de alta resolución de la NOAA (Reynolds et al., 2007). Este conjunto de datos tiene una resolución de 0,25° × 0,25°. Los datos de salinidad diarios de 1987 a 2020 se obtuvieron del Servicio de Monitoreo del Medio Marino de Copernicus (Simoncelli et al., 2014). Este conjunto de datos tiene una resolución de 0.063° × 0.063°. También se obtuvieron datos de Daily Chlorophyll- A del sitio web de Copernicus. Estos datos tienen una resolución espacial de 1 km × 1 km y van de 1997 a 2020 (disponibles en GOS-ISAC-CNR, Volpe et al., 2012). Los datos de viento diarios con una resolución de 2,5° × 2,5° (componentes u, oeste-este y v, sur-norte) se obtuvieron de la reanálisis del NCEP, del sitio web del PSD de la NOAA/OAR/ESRL, Boulder, Colorado, EE. UU., en https://www.esrl.noaa. gov/psd/ (Kalnay et al., 1996). Se consideró que la AJ en el estrecho de Gibraltar era otra variable ambiental con el potencial de afectar a los peces pelágicos pequeños. Sin embargo, las series temporales largas para esta variable no están disponibles. Para evitar esta limitación, y según García-Lafuente et al. (1998) y Vargas-Yáñez et al. (2002), se puede considerar que la AJ está en equilibrio geostrófico con la diferencia del nivel del mar a través del Estrecho. Según esta expresión, la diferencia entre el nivel del mar entre Algeciras y Ceuta puede considerarse un buen indicador de los cambios en la velocidad de entrada. Las series temporales mensuales del nivel del mar para Algeciras y Ceuta se obtuvieron de la red de mareógrafos del Instituto Español de Oceanografía y del Servicio Permanente del Nivel Medio del Mar (www.psmsl.org).

Se construyeron series temporales mensuales para la diferencia del nivel del mar a través del Estrecho de 1981 a 2020. Por último, los principales patrones de circulación atmosférica en el Atlántico Norte y el Mar Mediterráneo pueden influir en la productividad de las aguas mediterráneas, además de en la distribución y abundancia del plancton (García-Comas et al., 2011; Fernández de Puelles et al., 2007) y de los organismos de alto nivel trófico (Hidalgo et al., 2011, 2015). Los índices NAO anuales y de invierno (de diciembre a marzo) se obtuvieron del Centro Nacional de Investigación Atmosférica (2017). El índice NAO se define como la diferencia normalizada de presión del nivel del mar entre las Azores e Islandia. El Índice de Oscilación del Mediterráneo (MOI) se define como la diferencia normalizada de presión del nivel del mar entre Gibraltar e Israel. Los valores del MOI se obtuvieron de la Unidad de Investigación Climática de la Universidad de East Anglia. El índice de oscilación del Mediterráneo occidental es más local y se define como la diferencia de presión entre San Fernando, en el Golfo de Cádiz, España, y Padua, en el norte de Italia (Martín-Bide y López-Bustins, 2006). Estos datos se obtuvieron del Grupo de Climatología de la Universidad de Barcelona (www.ub.edu/gc/en).

Se agregaron los desembarques mensuales desde los puertos de Mdiq, Hoceima, Nador y Ras Kebdana. La alta variabilidad en las series temporales mensuales de los desembarques de sardinas está fuera del alcance de este estudio actual. Por lo tanto, las series temporales mensuales se promediaron anualmente, es decir, se promediaron los valores doce mensuales de cada año. De esta forma, obtuvimos un punto de datos por año. Muchos estudios han demostrado que las LPUE son un indicador apropiado de la abundancia de diferentes especies. Ruiz et al. (2013) utilizaron el LPUE para estimar la variabilidad de la abundancia de anchoas en el mar de Alborán, Thiaw et al. (2017) usaron el LPUE como indicador de la abundancia de Sardinella en la costa noroccidental de África, y Massutí et al. (2008) e Hidalgo et al. (2011) lo usaron para analizar la merluza europea en el mar Balear. Sin embargo, los datos sobre los esfuerzos de pesca de la flota que se dedica a la sardina en aguas marroquíes de Alborán solo estarán disponibles a partir de 2009. Esto reduce considerablemente la longitud de las series temporales analizadas y la posibilidad de encontrar relaciones significativas con las variables ambientales. Utilizar los desembarques en lugar de la LPUE aumentaría la longitud de las series temporales disponibles, pero los cambios en los desembarques de sardinas podrían ser simplemente el resultado de cambios en el esfuerzo de pesca y no ser un reflejo de la variabilidad real en la abundancia de las poblaciones.

Para comprobar esta posibilidad, se realizó un análisis de regresión entre los desembarques y el LPUE tanto para la serie temporal anual como para la mensual, que reveló una correlación alta y significativa en ambos casos, lo que respaldó el uso de los aterrizajes como variable de respuesta. Este resultado indica que la variabilidad de la abundancia de los peces pelágicos pequeños en el sur del mar de Alborán podría describirse a través de los datos de desembarque. Este resultado coincide con el alto nivel de correlación entre los desembarques y el LPUE para el sector norte del mar de Alborán. Esta estrecha relación entre los desembarques y la LPUE ya se ha demostrado en los desembarques de sardinas juveniles en Vigo (costa ibérica atlántica, Guisande et al., 2004) y el puerto de Tarragona (noroeste del Mediterráneo, Lloret et al., 2004). Para los datos ambientales, el SST, el SSS y el CHL-a de superficie se procesaron de dos formas diferentes. Los datos se distribuyeron en cuadrículas regulares con diferentes resoluciones. Para describir las fluctuaciones en las variables que afectan directamente al sur del mar de Alborán, se seleccionaron puntos de la cuadrícula comprendidos entre 5,5° O y 2° O y al sur de 36° N y se promediaron anualmente. De esta forma, se obtuvieron series temporales anuales para SST, SSS y CHL-a para la mitad sur del mar de Alborán. El cálculo directo de los valores medios para el sur del mar de Alborán nos permite analizar las relaciones entre los desembarques de sardinas de este sector y las variables ambientales observadas en la misma área geográfica. Sin embargo, el mar de Alborán tiene una hidrodinámica altamente energética. La producción primaria, o las distribuciones del fitoplancton y el zooplancton, que pueden afectar a las poblaciones de peces en determinadas regiones (Brosset et al., 2015, 2016, 2017), podría ser el resultado de la advección y otros procesos que se producen en lugares cercanos. Hay disponible una serie temporal de SST, SSS y CHL-a para cada punto de la cuadrícula (latitud/longitud) dentro del área geográfica seleccionada (Mar de Alborán). Estas series temporales no son estadísticamente independientes y la variabilidad en cada punto de la cuadrícula puede considerarse el resultado de la variación en varias estructuras espaciales. Cada una de estas estructuras espaciales es un EOF.

Las tendencias lineales se estimaron ajustando una línea recta a todas las series temporales (desembarques de sardinas y predictores ambientales) mediante el ajuste mínimo cuadrado. La pendiente representa la tasa media anual de cambio. Se obtuvieron intervalos de confianza con un nivel de confianza del 95% para la pendiente teniendo en cuenta la distribución t de Student tras comprobar la normalidad de los residuos (pruebas de Kolmogorov-Smirnov, véase Zar, 1984, por ejemplo).

Todos los cálculos involucrados en la selección del modelo se repitieron utilizando series temporales originales y no tendidas. Si bien todas las variables ambientales descritas anteriormente se basan en conocimientos científicos sólidos, el número de predictores utilizados para modelar la variabilidad de los desembarques de sardinas debe mantenerse lo más bajo posible, de acuerdo con los grados de libertad del análisis (Burnham y Anderson, 2002). Por este motivo, se llevó a cabo un primer análisis exploratorio de los datos. Se analizaron gráficos de dispersión de SST, SSS, Chla, SLD e índices climáticos (NAO, MOI, WeMo) en comparación con los desembarques de sardinas.

Se realizó el mismo análisis para los principales modos de variabilidad de SST, SSS y CHL-a. Los desembarques de sardinas se redujeron en función de estas variables, y solo las que se correlacionaban significativamente en el nivel de significancia de 0,1 se consideraron posibles predictores para la generación de modelos lineales candidatos. Se descartaron las variables que no se correlacionaban significativamente. Este análisis se consideró para las variables ambientales ya descritas, con y sin un desfase de un año. En este primer análisis, se utilizaron las series temporales completas, es decir, no se restó ninguna tendencia ni de los desembarques de sardinas ni de las variables predictoras. El procedimiento para seleccionar el mejor modelo de aproximación fue el siguiente (Vargas-Yáñez et al. 2009): se suprimió un año de la serie temporal (tanto de respuesta como de predictores). Se aplicó una regresión lineal múltiple a los datos n-1 restantes. Se usó un procedimiento gradual hacia adelante y se calcularon los valores F parciales para cada predictor en cada etapa. Se utilizó una probabilidad de p = 0,05 para introducir un nuevo predictor en el modelo y p = 0,1 para eliminarlo (véase, por ejemplo, Draper y Smith, 1981). La colinealidad entre los predictores se comprobó mediante el factor de inflación de la varianza (VIF), que fue inferior a 3 para todos los predictores y modelos considerados. Este procedimiento se repitió n veces (cada vez se suprimieron datos diferentes de la serie temporal original). Para cada paso, se seleccionó un modelo diferente para la regresión escalonada hacia adelante y este se consideró un modelo candidato.

Finalmente, una vez que se seleccionó un conjunto de modelos candidatos, se aplicó una regresión lineal múltiple a cada modelo candidato y a la serie temporal completa (n datos). Los AICc (Criterios de información de Akaike corregidos) se calcularon según Burnham y Anderson (2002). Finalmente, se seleccionó el modelo candidato con el AICc mínimo como el mejor modelo de aproximación.

Una vez seleccionado el modelo final, se aplicó un procedimiento de validación cruzada (Francis 2006; Lavín et al. 2007; Vargas-Yáñez et al. 2009). Utilizando el modelo seleccionado, se estimaron los aterrizajes de cada año de la serie temporal utilizando los datos n-1 restantes y se comprobó la predicción con la estimación predeterminada, que se consideró el valor medio de la serie temporal (utilizando los datos n-1 para la estimación). Para analizar la relación entre los desembarques de sardinas y las variables ambientales únicamente en una escala temporal interanual, se eliminaron las tendencias de los desembarques de sardinas y los posibles predictores (con y sin desfase temporal). Por ejemplo, los desembarques de sardinas se consideraron una tendencia lineal, que representaba los cambios a largo plazo, más un término que representaba la variabilidad interanual.

Los resultados del modelado fueron muy diferentes para cada especie; por ejemplo, si las tendencias no se eliminan de las series temporales de aterrizaje de sardinas y ambientales, el modelo lineal mejor elegido relaciona el aterrizaje de sardinas con el SST del año anterior, el cuarto patrón de salinidad (del análisis de componentes principales) y el SLD el mismo año del aterrizaje (sin demora). También vale la pena enfatizar que existe una relación negativa entre los aterrizajes y la SST. Se podría argumentar que las tendencias positivas al calentamiento son en parte responsables de la tendencia a la baja en las capturas de sardinas. La relación entre los desembarques y el SLD podría indicar que una tendencia negativa en el SLD induce una tendencia negativa en los desembarques de sardinas. La posibilidad de una correlación entre los pequeños peces pelágicos y la energía cinética del AJ entrante no es una hipótesis nueva. El AJ con alta energía cinética aumentaría la producción primaria en el norte del mar de Alboran, pero también aumentaría la dispersión de las larvas, lo que afectaría negativamente a la supervivencia de las larvas y al reclutamiento anual de anchoas. En el sur del mar de Alborán, hubo una relación positiva entre la velocidad de AJ y la abundancia de sardinas, y una velocidad más alta se asoció con una mayor abundancia y viceversa.

Finalmente, un cuarto patrón de salinidad se asoció negativamente con los desembarques de sardinas. Sin embargo, esta asociación solo puede estar relacionada con la variabilidad interanual. Este patrón de cambio no mostró una tendencia general significativa, a pesar de una tendencia positiva en la salinidad media en toda la región.

Además de los posibles efectos de los cambios de temperatura y SLD a largo plazo en la disminución de los desembarques de sardinas, el modelo lineal elegido pudo reproducir las variaciones a largo plazo e interanuales en los desembarques de sardinas y explicó el 64% de la varianza de las observaciones. Una segunda posibilidad considerada en este trabajo es eliminar la tendencia lineal de las variables de respuesta y predictora. En este enfoque, una tendencia lineal se determina ajustando una línea recta a la serie temporal de aterrizaje, y los residuos representan los cambios anuales en torno al comportamiento lineal. Este enfoque no puede explicar la disminución a largo plazo de las capturas de sardina, y el modelo evalúa el impacto de las fluctuaciones anuales en las variables ambientales. Se obtuvieron dos modelos posibles: un modelo correlacionó positivamente los residuos de aterrizaje con las concentraciones de CHL-a con un desfase de un año (coeficiente 1838 t mg de CHL-A -1 m -3) y con SLD (coeficiente 8 t mm -1). En este modelo, también existe una correlación positiva entre el aterrizaje, la clorofila y el SLD y el primer modelo. Por lo tanto, los resultados de estos dos modelos sugieren que el aumento de las concentraciones de CHL-a en el año anterior o durante el año en que se registraron las capturas de sardina afectó positivamente a la abundancia de sardina. Además, la energía cinética del AJ entrante parece ser un factor importante. En todos los casos, se obtuvieron resultados muy similares, con un aumento/disminución de unas ocho toneladas por cada aumento o disminución de 1 mm de SLD a través del estrecho. Cuando se reconstruyeron las series temporales de desembarques de sardinas utilizando la tendencia lineal estimada y el modelo lineal de los residuos o detendencias.

Además de las variaciones a largo plazo e interanuales en los desembarques de sardinas, también se pusieron de manifiesto las variaciones estacionales mediante el promedio de desembarques de cada mes del año calculado utilizando toda la serie temporal. Este ciclo estacional muestra los desembarques mínimos del período de febrero a abril. La temperatura media de la superficie del mar para estos meses también se calculó a partir de los datos satelitales utilizados en este estudio; estos valores oscilan entre 15,5 °C y 16,5 °C. Los máximos de aterrizaje se registraron de octubre a enero, lo que muestra un patrón claro y recurrente de aterrizajes máximos en otoño, lo que probablemente refleje la reposición de sardinas que se completa cada septiembre. Como la época de reproducción de las sardinas es entre enero y marzo, se puede suponer que los desembarques mínimos corresponden a la temporada de desove.

A partir de los datos disponibles, se puede sugerir que la temporada de reproducción en el sur del mar de Alborán se retrasa en comparación con la cercana costa atlántica y el norte del mar de Alborán, o simplemente que los desembarques mínimos corresponden a unos días después del desove. Ya que la temporada de reclutamiento (con una probabilidad mucho mayor de capturas) tendrá lugar en los próximos meses. En el caso de la anchoveta, utilizando series temporales de tendencias, los factores ambientales explicaron entre el 60 y el 79% de la varianza total en los desembarques de anchoveta, y la mayoría de los modelos resultantes fueron estadísticamente significativos. La temperatura, la salinidad y el componente del viento en U mostraron una asociación negativa con los desembarques de anchoas. Por otro lado, la velocidad de los Atlantic Jets al viajar por el Estrecho de Gibraltar se correlacionó positivamente con los desembarques de anchoas.

Lamentablemente, la mayoría de los factores ambientales y los desembarques de anchoas en el Mediterráneo han mostrado tendencias claras, lo que puede subrayar las correlaciones observadas en nuestro modelo. Al utilizar series temporales ajustadas por tendencias, no se encontró ninguna asociación entre la frecuencia de la anchoveta y las variables ambientales. Por lo tanto, si bien el SST, el SSS, el U y el V se pueden utilizar para predecir la abundancia de anchoas a lo largo de los ciclos estacionales, no pueden predecir las tendencias a largo plazo. Esto puede deberse a dos factores: los datos ambientales no muestran una tendencia significativa durante el período analizado (38 años), y hay otros factores más importantes que influyen en la disminución de la abundancia de anchoa en el sur del mar de Alborán, como el aumento de la presión pesquera sobre las especies objetivo más importantes.

Para el caso de la caballa, utilizando los datos originales, se seleccionó la salinidad de la superficie del mar para todos los modelos, por lo que este factor es el factor más importante de la caballa del Atlántico en esta región. De hecho, el SSS sigue siendo el predictor más importante después de utilizar las series temporales con tendencia reducida. Hubo una correlación positiva con los desembarques de caballa, lo que sugiere que esta especie prefiere una salinidad más alta y que los recientes aumentos de la salinidad en la región tuvieron un impacto positivo en esta especie.

Las adaptaciones fisiológicas de la caballa para soportar las variaciones de salinidad son probablemente las que contribuyen a los efectos beneficiosos del SSS sobre ella. En particular, A. mackerel puede controlar sus fluidos corporales para mantener el equilibrio osmótico en diferentes salinidades y tiene una alta tolerancia al agua salada. Como resultado, aumentar el SSS puede ser ventajoso para esta población de especies. De hecho, la salinidad no afecta a esta especie, pero sí pone de relieve un proceso de fertilización del agua más complejo, ya que estaba relacionado con una masa de agua más rica en nutrientes que entraba en el Golfo de Vizcaya. Por ejemplo, un aumento de la salinidad en nuestra región de estudio podría indicar una mayor intensidad de afloramiento en el mar de Alborán.

El segundo predictor más común en los modelos fue el desembarque de anchoas. Por alguna razón, esta otra especie pelágica pequeña se correlacionó positivamente con la caballa tanto en la serie temporal original como en la serie temporal con tendencia decreciente. Esta asociación positiva no se observó ya que la captura de sardina no se seleccionó en ningún modelo significativo. Según los resultados de nuestro estudio, la captura de anchoas también sirvió como un predictor significativo. Esta conclusión puede explicarse por la posibilidad de que estas dos especies coexistan en el mismo hábitat o por la estrecha relación entre sus respectivas tasas de captura. Como estas dos especies no compiten por la presa, la caballa se podría alimentar de esta especie.

Además de eso, varios estudios han informado de una relación positiva entre la abundancia de anchoa y caballa, lo que indica que estas dos especies coexisten y comparten nichos ecológicos similares en el ecosistema marino. Además, se sabe que la caballa se alimenta de anchoas, pero también su área de alimentación incluye peces de tres grupos ecológicos. Los juveniles de especies epipelágicas masivas, como la sardinela redonda, el jurel de Cunene, la anchoa europea y la sardina europea, se incluyeron en la primera categoría. Las especies mesopelágicas de las familias Paralepididae y Myctophidae formaron el segundo grupo. Las especies bentónicas y de fondo son el tercer grupo. Los crustáceos y el zooplancton han sido las fuentes alimenticias secundarias del cacho atlántico. La distribución y abundancia de la caballa atlántica y sus presas pueden estar influenciadas por una amplia gama de condiciones ambientales. Como especie objetivo importante, es importante entender las interacciones físicas y tróficas que desencadenan su abundancia y cómo los diferentes escenarios de cambio climático podrían afectar la abundancia de A. mackerel.

El SLD, que representa la corriente atlántica rica en nutrientes y CHL-A del Estrecho de Gibraltar, parece ser otro factor limitante para la caballa, ya que los niveles más altos conducen a que una corriente atlántica más rica en nutrientes entre en el mar de Alborán. Esto podría explicarse por el efecto de fertilización de AJ. Los chorros del Atlántico que fluyen hacia la región tienen un impacto sustancial en los animales que residen en el mar de Aborán, especialmente en las especies de peces pelágicos pequeños. Estos chorros extraen agua del Atlántico que se fertiliza debido a los procesos de mezcla dentro del Estrecho de Gibraltar, lo que aumenta la producción primaria y, a su vez, el número de peces pelágicos pequeños.

La temperatura de la superficie del mar es el cuarto parámetro ambiental seleccionado. Se seleccionó utilizando solo la serie temporal completa, no el conjunto de datos sin tendencia. Este factor también mostró una asociación positiva con las especies, pero se ignoró debido a la disminución de la tendencia de los datos, lo que sugiere que el efecto de este factor en la especie solo se produjo en una escala interanual (estacional). La abundancia y dispersión de la caballa pueden beneficiarse del aumento de las temperaturas. El rango de temperatura ecológica de la caballa tiende a moverse más hacia el norte a medida que aumentan las temperaturas, lo que presenta a la especie mejores condiciones climáticas. El calentamiento de los océanos provocado por el cambio climático puede provocar un posible aumento de A. mackerel. Esto es cierto en nuestro caso, ya que el aumento o el aumento de la temperatura de la superficie del mar mostró una relación positiva con el aumento del aterrizaje de esta especie.

Por otro lado, los vientos U y V se seleccionaron utilizando únicamente las series temporales con tendencia reducida y muestran dos efectos opuestos. Se observaron correlaciones positivas en la caballa con el viento en V, lo que puede indicar que los vientos del norte tienen un efecto positivo en la abundancia de la caballa. Por lo tanto, la velocidad y la dirección del viento también pueden tener un impacto considerable en las pequeñas especies pelágicas. Los cambios en la velocidad del viento pueden afectar a las corrientes oceánicas, lo que puede alterar la distribución de los recursos alimentarios y el movimiento de las larvas y los huevos. Por ejemplo, el aumento de la velocidad del viento puede aumentar la mezcla de las columnas de agua, lo que reduce las concentraciones de fitoplancton y la cantidad de alimento a los que tienen acceso las especies de caballa. Según nuestros hallazgos, existe una sorprendente asociación negativa entre los componentes ambientales CHL-a (indicador de producción primario) y el aterrizaje de la especie. Este componente tiene un coeficiente de correlación negativo y solo se incluyó dos veces en los modelos.

En conclusión, podemos ver lo difícil que es modelar la reacción de estas pequeñas especies pelágicas a los cambios ambientales. Además, es muy difícil predecir con precisión cómo afectará el cambio climático a las pequeñas especies pelágicas debido a la falta de planes de monitoreo establecidos a largo plazo, la escasez de datos, los complejos cambios ambientales y la sobrepesca.

Por eso es tan importante realizar más estudios interdisciplinarios para tratar de comprender completamente cómo el cambio ambiental y la pesca impactan en el funcionamiento del ecosistema en general, y en la dinámica y la población de las pequeñas especies pelágicas en particular.

Résumé

Le changement climatique devrait déplacer la plupart des communautés d'espèces terrestres et marines vers les pôles. En effet, la température est un facteur clé de la répartition des animaux marins en raison de la tolérance directe (par exemple le métabolisme, en particulier la tolérance aux stades larvaires planctoniques) et indirects (par exemple substitution d'autres conditions environnementales, distribution prédateur-proie) (en particulier au stade larvaire planctonique) qui se manifeste par des changements latitudinaux ou une expansion/contraction de l'habitat, en particulier pour les espèces mobiles telles que les poissons. Par exemple, les espèces benthiques voient leur latitude moyenne, leur profondeur (ou les deux modifiées). Sur une période de 25 ans, en réponse au récent élargissement de la marge de la mer du Nord. La frontière s'est déplacée vers le nord en raison du réchauffement, mais les différences de vitesse de déplacement entre les espèces ont accéléré le déplacement des espèces migratrices et ont réduit leur cycle de vie. (Southward et coll., 1995 ; Parmesan et Yohe, 2003 ; Beaugrand et Ibáñez, 2004).

Par exemple, le changement climatique peut également modifier les structures du plancton et des communautés de poissons. En fait, Boyd et Doney (2002) concluent que les changements régionaux sont aussi importants que les changements de productivité à grande échelle. Les variations saisonnières de la biomasse et du phytoplancton dominant au cours de la transition subarctique et subtropicale étaient liées au réchauffement climatique dans toutes les régions.

Ces modifications du phytoplancton peuvent fournir des explications supplémentaires ou complémentaires aux modifications à grande échelle de la biogéographie du zooplancton dans de nombreux endroits en réponse aux modifications des zones climatiques (Beaugrand et al., 2002).

Par exemple, la mer de Béring a connu des changements importants depuis 1990 environ, ce qui a donné lieu à des spéculations quant à savoir si l'augmentation de la biomasse des méduses était le résultat de perturbations humaines. Cependant, les niveaux maximaux de zooplancton gélatineux dans la mer de Béring ont diminué de manière significative et sont restés faibles depuis 2000 (King. 2005). On ne sait donc toujours pas si les efflorescences des années 1990 étaient liées à des tendances à long terme ou à des événements isolés. Dans le golfe de Gascogne, de nombreuses espèces de poissons vivent à la limite sud ou nord de leur aire de répartition, et le récent changement climatique a modifié la structure des communautés de poissons. Dans le groupe à tendance négative, un tiers (sept) des espèces étaient caractérisées par une répartition nordique et une étroite répartition latitudinale.

Un autre groupe de biomasse comprend principalement des espèces en transition sans tendance à long terme. Dans l'ensemble, de nombreuses espèces de poissons se trouvent à la limite sud ou nord de leur aire de répartition, et les récents changements climatiques ont modifié la structure de la communauté de poissons dans cette baie (Poulard et Blanchard, 2005).

L'impact de la poursuite du réchauffement sur la pêche commerciale à la morue, au flet, au merlan bleu ou au sébaste se traduit par des modifications continues de la distribution ainsi que par des modifications des réseaux alimentaires. Par exemple, des taux de déplacement différents peuvent entraîner des modifications du chevauchement spatial entre les espèces, perturbant notamment les interactions. Des études menées par GLOBEC entre 2003 et 2005 ont fait état d'une augmentation soudaine du nombre d'espèces pélagiques de sardines d'eau chaude (Pilchardus) dans le nord-ouest de la mer du Nord, ce qui suggère que les anchois et les sardines frayent désormais dans le sud de la mer du Nord. Cette augmentation serait davantage liée au rétablissement des populations de sardines près de la Californie qu'au fait de permettre aux sardines de migrer vers la mer du Nord en raison du réchauffement des eaux (Voss et al., 2009). Un exemple d'effet direct de la température sur le recrutement est donné par Planque et Fredou (1999), qui ont étudié le recrutement de la morue dans différentes régions de l'océan.

Dans les régions où les températures sont inférieures à la température optimale pour la morue, Drinkwater (2005) a utilisé les changements prévus dans le champ de température et les réponses connues observées de la morue aux changements de température pour estimer la réponse des stocks de morue de l'Atlantique Nord. On pense que certains océans pourraient disparaître d'ici 2100 en raison des changements de température prévus, avec le recul de certaines zones du sud de la mer du Nord et de George Shoal. Selon Drinkwater (2005), la réponse au changement climatique futur est très incertaine et dépend de l'évolution d'autres variables climatiques et océaniques autres que la température, telles que la croissance induite par l'hypothèse de « la température de croissance optimale » pour expliquer le changement climatique au changement de régime de certaines petites espèces pélagiques (par exemple, la sardine et l'anchois). Ils suggèrent que cette variation est due à des différences de température optimale pour le taux de croissance au début de la vie, les anchois ayant une température optimale plus élevée (22 °C) que les sardines (16 °C). Entre les températures optimales, il peut y avoir des fluctuations des taux de croissance des deux espèces et des changements dans l'occurrence de l'espèce dans l'ouest du Pacifique Nord. Quels que soient les processus sous-jacents, la poursuite du changement climatique devrait amplifier de manière correspondante ces différences géographiques en matière de recrutement, entraînant des modifications de la répartition des espèces, en particulier pour certaines espèces clés vulnérables telles que les petites espèces pélagiques.

Les petites espèces pélagiques jouent un rôle très important dans la pêche commerciale, représentant 22 % des captures marines mondiales (FAO, 2011). C'est le cas pour la Méditerranée et la mer Noire où les anchois (393 500 tonnes/an) et les sardines (186 100 tonnes/an) sont les espèces dominantes, représentant 26 % et 12 % des captures totales (FAO, 2016). Ces espèces jouent un rôle clé dans les écosystèmes marins en raison de leur biomasse élevée et de leur rôle dans la liaison entre les niveaux trophiques inférieurs et supérieurs (Bakun, 1996). Les petits poissons pélagiques à croissance rapide, à maturation précoce et à faible classe d'âge reproducteur sont très vulnérables aux changements environnementaux en raison de leur forte dépendance à l'égard de l'hydroclimatologie souterraine et de la variabilité spatiale et temporelle de la production primaire (Brosset et al., 2015, 2016, 2017 ; Hidalgo et al., 2011 ; Lloret et al., 2004).

Un autre facteur affectant ces espèces est l'augmentation de l'effort de pêche. Les captures connaissent des tendances négatives suggérant un possible déclin des stocks (GFCM, 2016). Pinsky et al. (2011) ont démontré que la probabilité d'effondrement de ces pêcheries est similaire à celle observée pour les espèces de grande taille et à maturité tardive. Le changement climatique est reconnu comme une autre menace potentielle pour les ressources marines exploitées (FAO, 2008), les changements de température de la mer pouvant modifier la biologie des espèces marines, leurs cycles saisonniers et leur distribution.

Ces changements pourraient avoir un impact plus important sur les espèces de petite taille à croissance rapide, comme les petits poissons pélagiques (Perry et al., 2005). En raison de ses dimensions réduites par rapport aux océans du monde et de son caractère semi-fermé, la mer Méditerranée pourrait être particulièrement sensible au changement climatique (Garcia-Martinez et al., 2018 ; Vargas-Yáñez et al., 2017 ; Bethoux et al., 1999). Tugores et al. (2011) ont montré l'impact de variables environnementales telles que la température, la salinité et la concentration de chlorophylle sur l'adéquation de l'habitat de la sardine et la rayonne Baud et al. (2017) ont suggéré que le changement climatique pourrait entraîner une diminution modérée de l'abondance des anchois au cours du 21e siècle. Brosset et al. (2017) ont constaté une diminution de l'état corporel des anchois et des sardines, mais cela n'a pas pu être lié aux principaux indices climatiques. Ces auteurs ont suggéré que les changements environnementaux régionaux et leur impact sur les assemblages phytoplanctoniques et zooplanctoniques pourraient être liés à cette diminution de l'état corporel par le biais de mécanismes de contrôle ascendants (Brosset et al., 2015, 2016). Sabatés et al. (2006, 2009) ont montré que le réchauffement de l'eau de mer était responsable de la modification de la distribution de Sardinella aurita, qui s'était étendue vers le nord jusqu'au nord-ouest de la Méditerranée (plateau catalan).

Les espèces marines étant l'une des espèces les plus touchées par ces changements environnementaux, nous devons nous rappeler que ces effets peuvent avoir un impact significatif sur l'économie de certains pays qui dépendent des activités de pêche, comme le Maroc. En effet, la pêche marocaine capture plus de 1,42 million de tonnes d'espèces marines commerciales, génère un chiffre d'affaires de plus de 15 milliards de dirhams, représente 2 % du PIB et emploie environ 360 000 personnes directement ou indirectement (DPM, 2021). Historiquement, les petites espèces pélagiques représentent l'essentiel du potentiel halieutique du Maroc, représentant 80 % de la production de poissons.

Les petites ressources pélagiques comprennent principalement des espèces de clupéidés (*Sardina pilchardus, Sardinella aurita et Sardinella madarensis*), des scombridés *(Scomber colias*), des carangides (*Trachurus trachurus, Trachurus trecae* et *Trachurus mediterraneus*) et des engraulides (*Engraulis encrasicolus*) (INRH, 201).

La pêche aux petites espèces pélagiques étant la principale activité en Méditerranée. Cette activité s'est intensifiée au cours des deux dernières décennies, ce qui a entraîné une augmentation des interactions entre les principaux prédateurs et les senneurs de la région. Les groupes de grands dauphins attaquent les bateaux de pêche tout en encerclant des poissons pélagiques tels que les sardines et les anchois, causant d'énormes pertes économiques aux pêcheurs et exposant ces espèces protégées à un risque élevé de blessures (Malouli et al., 2020).

Bien que le déclin de cette petite pêche pélagique soit principalement dû à la pêche, le changement climatique et son impact sur la perturbation de l'écosystème marin peuvent également avoir affecté ces espèces, d'autant plus que la mer Méditerranée est une zone semi-fermée et très sensible aux changements environnementaux (Abdellaoui et al., 2017 ; MM Garcia et al., 2018). En fait, les raisons de ce déclin ont été largement débattues par les pêcheurs marocains, qui affirment que leurs activités ne sont pas la cause principale de ce déclin, et que de nombreuses recherches ont été menées sur l'évolution de ces stocks de poissons, ainsi que sur les impacts de la pêche (suivis annuellement par l'INRH), mais très peu d'études ont tenté de comprendre la relation entre la dynamique de ces espèces et l'évolution des conditions océanographiques dans la région (Abdellaoui et al., 2017 ; Jghab et al., 2019 ; Vargas et al., 2020 ; INRH, 2016).

Dans notre étude, les données sur les principaux débarquements mensuels de petits poissons pélagiques (sardines, anchois et maquereaux) sur la côte méditerranéenne marocaine entre 1983 et 2020 ont été obtenues auprès de l'Office national des pêches du Maroc. Pour les principaux ports de pêche pélagique, Mdiq, Hoceima, Nador et Ras Kebdana, bien que d'autres ports plus petits contribuent également au total des débarquements de sardines dans cette zone (moins de 1 %). L'effort de la flotte (jours de pêche) n'était disponible que de 2009 à 2020. Les débarquements par unité d'effort (LPUE) pour cette période ont été estimés en tonnes métriques divisés par le nombre de jours de pêche.

Outre les débarquements de petites espèces pélagiques, des informations sur les variables environnementales susceptibles d'avoir une incidence sur le recrutement et l'abondance des sardines ont été obtenues auprès de diverses sources. Ces variables sont la température de surface de la mer (SST), la salinité de la surface de la mer (SSS), la concentration de chlorophylle-a en surface (CHL-a), les composantes ouest-est (u) et sud-nord (v) du vent, l'indice d'oscillation nord-atlantique (NAO), l'indice d'oscillation méditerranéenne (MOI) et l'indice d'oscillation de la Méditerranée occidentale (WeMo). Les données SST, SSS et CHL-a ont été moyennées sur la partie sud de la mer d'Alboran, de 5,5°W à 2°W et de 35°N à 36°N.

Les données quotidiennes sur la température de surface de la mer de 1981 à 2020 ont été obtenues à partir des données SST à haute résolution de la NOAA (Reynolds et al., 2007). Cet ensemble de données a une résolution de 0,25° × 0,25°. Les données de salinité quotidiennes de 1987 à 2020 ont été obtenues auprès du service de surveillance de l'environnement marin Copernicus (Simoncelli et al., 2014). Ce jeu de données a une résolution de 0,063° × 0,063°. Des données quotidiennes sur la chlorophylle-A ont également été obtenues sur le site Web de Copernicus. Ces données ont une résolution spatiale de 1 km × 1 km et s'étendent de 1997 à 2020 (disponibles auprès de GOS-ISAC-CNR, Volpe et al., 2012). Les données sur les vents quotidiens avec une résolution de 2,5° × 2,5° (u, ouest-est et v, composantes sud-nord) ont été obtenues à partir de la réanalyse du NCEP, à partir du site Web de la NOAA/OAR/ ESRL PSD, Boulder, Colorado, États-Unis à l'adresse https://www.esrl.noaa. gov/psd/ (Kalnay et al., 1996). L'AJ dans le détroit de Gibraltar a été considéré comme une autre variable environnementale susceptible d'avoir un impact sur les petits poissons pélagiques. Toutefois, les séries chronologiques longues pour cette variable ne sont pas disponibles. Pour contourner cette limite, et selon García-Lafuente et al. (1998) et Vargas-Yáñez et al. (2002), l'AJ peut être considéré comme étant en équilibre géostrophique avec la déférence du niveau de la mer entre les deux rives du détroit. Selon cette expression, la différence entre le niveau de la mer d'Algésiras et de Ceuta peut être considérée comme un bon indicateur des variations de la vitesse d'afflux. Les séries chronologiques mensuelles du niveau de la mer pour Algésiras et Ceuta ont été obtenues à partir du réseau marégraphique de l'Instituto Español de Oceanografía et du Service permanent du niveau moyen de la mer (www.psmsl.org). Des séries chronologiques mensuelles pour la déférence du niveau de la mer entre les deux rives du détroit ont été établies pour la période allant de 1981 à 2020. Enfin, les principaux modèles de circulation atmosphérique dans l'Atlantique Nord et la mer Méditerranée peuvent influencer la productivité des eaux méditerranéennes, en plus de la distribution et de l'abondance du plancton (García-Comas et al., 2011 ; Fernández de Puelles et al., 2007) et des organismes de haut niveau trophique (Hidalgo et al., 2011, 2015). Les indices hivernaux (décembre à mars) et annuels de la NAO ont été obtenus auprès du National Centre for Atmospheric Research (2017). L'indice NAO est défini comme la différence de pression normalisée au niveau de la mer entre les Açores et l'Islande. L'indice d'oscillation méditerranéen (MOI) est défini comme la différence de pression normalisée au niveau de la mer entre Gibraltar et Israël. Les valeurs MOI ont été obtenues auprès de l'unité de recherche sur le climat de l'université d'East Anglia. L'indice d'oscillation de la Méditerranée occidentale est plus local et défini comme la différence de pression entre San Fernando, dans le golfe de Cadix, en Espagne, et Padoue, dans le nord de l'Italie (Martín-Bide et López-Bustins, 2006). Ces données ont été obtenues auprès du groupe de climatologie de l'université de Barcelone (www.ub.edu/gc/en).

Les débarquements mensuels en provenance des ports de Mdiq, Hoceima, Nador et Ras Kebdana ont été agrégés. La grande variabilité des séries chronologiques mensuelles des débarquements de sardines dépasse le cadre de la présente étude. Par conséquent, les séries chronologiques mensuelles ont fait l'objet d'une moyenne annuelle, en d'autres termes, les valeurs sur douze mois pour chaque année ont été moyennées. Nous avons ainsi obtenu un point de données par an. De nombreuses études ont montré que les LPUE constituent un indicateur approprié de l'abondance de déférentes espèces. Ruiz et al. (2013) ont utilisé le LPUE pour estimer la variabilité de l'abondance des anchois dans la mer d'Alboran, Thiaw et al. (2017) ont utilisé le LPUE comme indicateur de l'abondance de SARDINELLA le long de la côte nord-ouest de l'Afrique, et Massutí et al. (2008) et Hidalgo et al. (2011) l'ont utilisé pour analyser le merlu européen dans la mer des Baléares. Néanmoins, les données relatives à l'effort de pêche de la flotte ciblant la sardine dans les eaux de l'Alboran marocain ne sont disponibles qu'à partir de 2009. Cela réduit considérablement la longueur des séries chronologiques analysées et la possibilité de trouver des relations significatives avec les variables environnementales. L'utilisation des débarquements au lieu du LPUE augmenterait la longueur des séries chronologiques disponibles, mais les variations des débarquements de sardines pourraient simplement être le résultat de modifications de l'effort de pêche et ne pas refléter la variabilité réelle de l'abondance du stock. Pour vérifier cette possibilité, une analyse de régression entre les débarquements et le LPUE a été entreprise pour les séries chronologiques annuelles et mensuelles, qui a révélé une corrélation élevée et significative dans les deux cas, appuyant l'utilisation des débarquements comme variable de réponse. Ce résultat indique que la variabilité de l'abondance des petits poissons pélagiques dans le sud de la mer d'Alboran pourrait être décrite à l'aide des données de débarquement. Ce résultat coïncide avec le niveau élevé de corrélation entre les débarquements et le LPUE pour le secteur nord de la mer d'Alboran. Cette relation étroite entre les débarquements et le LPUE a déjà été démontrée pour les débarquements de sardines juvéniles à Vigo (côte ibérique atlantique, Guisande et al., 2004) et dans le port de Tarragone (nord-ouest de la Méditerranée, Lloret et al., 2004). Pour les données environnementales, le SST, le SSS et le Chl-a de surface ont été traités de deux manières différentes. Les données ont été diffusées sur des grilles régulières à déférentes résolutions. Afin de décrire les fluctuations des variables affectant directement le sud de la mer d'Alboran, des points de grille situés entre 5,5° O et 2° O et au sud de 36° N ont été sélectionnés et moyennés annuellement. Ainsi, des séries chronologiques annuelles pour SST, SSS et CHL-a ont été obtenues pour la moitié sud de la mer d'Alboran. Le calcul direct des valeurs moyennes pour le sud de la mer d'Alboran nous permet d'analyser les relations entre les débarquements de sardines provenant de ce secteur et les variables environnementales observées dans la même zone géographique. Néanmoins, la mer d'Alboran possède un hydrodynamique très énergétique. La production primaire, ou les distributions du phyto- et du zooplancton, qui peuvent affecter les stocks de poissons dans certaines régions (Brosset et al., 2015, 2016, 2017) pourraient résulter de l'advection et d'autres processus se produisant dans les zones voisines. Une série chronologique de SST, SSS et CHL-a est disponible pour chaque point de la grille (latitude/longitude) dans la zone géographique sélectionnée (mer d'Alboran). Ces séries chronologiques ne sont pas statistiquement indépendantes et la variabilité à chaque point de la grille peut être considérée comme le résultat de la variation de plusieurs structures spatiales. Chacune de ces structures spatiales est un EOF.

Les tendances linéaires ont été estimées en traçant une ligne droite pour toutes les séries chronologiques (débarquements de sardines et prédicteurs environnementaux) au moyen de l'ajustement au moindre carré. La pente représente le taux annuel moyen de variation. Des intervalles de confiance au niveau de confiance de 95 % ont été obtenus pour la pente en tenant compte de la distribution t d'une distribution de Student après vérification de la normalité des résidus (tests de Kolmogorov-Smirnov, voir Zar, 1984 par exemple). Tous les calculs nécessaires à la sélection du modèle ont été répétés en utilisant à la fois des séries chronologiques originales et des séries chronologiques modifiées.

Bien que toutes les variables environnementales décrites ci-dessus soient basées sur des connaissances scientifiques solides, le nombre de prédicteurs utilisés pour modéliser la variabilité des débarquements de sardines doit être maintenu aussi bas que possible, selon les degrés de liberté de l'analyse (Burnham et Anderson, 2002). C'est pourquoi une première analyse exploratoire des données a été entreprise. Les diagrammes de dispersion des indices SST, SSS, Chla, SLD et climatiques (NAO, MOI, WeMo) par rapport aux débarquements de sardines ont été analysés.

La même analyse a été réalisée pour les principaux modes de variabilité du SST, du SSS et du CHL-a. Les débarquements de sardines ont été régressés en fonction de ces variables, et seules celles présentant une corrélation significative au niveau de significativité de 0,1 ont été considérées comme des prédicteurs potentiels pour la génération de modèles linéaires candidats. Les variables qui n'étaient pas corrélées de façon significative ont été écartées. Cette analyse a été prise en compte pour les variables environnementales déjà décrites, avec ou sans décalage d'un an. Dans cette première analyse, les séries chronologiques complètes ont été utilisées, c'est-à-dire qu'aucune tendance n'a été soustraite des débarquements de sardines ou des variables prédictives. La procédure de sélection du meilleur modèle d'approximation était la suivante (Vargas-Yáñez et al. 2009) : une année de la série chronologique (à la fois réponse et prédicteurs) a été supprimée. Une régression linéaire multiple a été appliquée aux données n-1 restantes. Une procédure progressive a été utilisée et des valeurs F partielles ont été calculées pour chaque prédicteur à chaque étape. Une probabilité de p = 0,05 a été utilisée pour entrer un nouveau prédicteur dans le modèle, et p = 0,1 pour le supprimer (voir, par exemple, Draper et Smith, 1981). La colinéarité entre les prédicteurs a été vérifiée au moyen du facteur d'inflation de la variance (VIF), qui était inférieur à 3 pour tous les prédicteurs et modèles considérés. Cette procédure a été répétée n fois (chaque fois que des données différentes ont été supprimées de la série chronologique d'origine). Pour chaque étape, un modèle différent a été sélectionné pour la régression progressive et il a été considéré comme un modèle candidat.

Enfin, une fois qu'un ensemble de modèles candidats a été sélectionné, une régression linéaire multiple a été appliquée à chaque modèle candidat et pour la série chronologique complète (n données). Les AICC (Corrected Akaike Information Criteria) ont été calculés selon Burnham et Anderson (2002). Enfin, le modèle candidat avec le minimum AICc a été sélectionné comme étant le meilleur modèle d'approximation.

Une fois le modèle final sélectionné, une procédure de validation croisée a été appliquée (Francis 2006 ; Lavín et al. 2007 ; Vargas-Yáñez et al. 2009). À l'aide du modèle sélectionné, les débarquements pour chaque année de la série chronologique ont été estimés à l'aide des données n-1 restantes, et la prédiction a été testée par rapport à l'estimation par défaut, qui a été considérée comme la valeur moyenne de la série chronologique (en utilisant les données n-1 pour l'estimation). Afin d'analyser la relation entre les débarquements de sardines et les variables environnementales uniquement sur une échelle de temps interannuelle, les tendances relatives aux débarquements de sardines et aux prédicteurs potentiels (avec et sans décalage temporel) ont été modifiées. Par exemple, les débarquements de sardines ont été considérés comme une tendance linéaire, représentant les changements à long terme, plus un terme représentant la variabilité interannuelle.

Les résultats de la modélisation étaient très différents pour chaque espèce. Par exemple, si les tendances ne sont pas éliminées des séries chronologiques relatives aux débarquements de sardines et à l'environnement, le modèle linéaire le mieux choisi relie le débarquement de sardines au SST de l'année précédente, au quatrième profil de salinité (issu de l'analyse en composantes principales) et au SLD la même année que le débarquement (sans délai). Il convient également de souligner qu'il existe une relation négative entre les atterrissages et le SST. On pourrait soutenir que les tendances positives au réchauffement sont en partie responsables de la tendance à la baisse des débarquements de sardines. La relation entre les débarquements et le SLD pourrait indiquer qu'une tendance négative du SLD entraîne une tendance négative des débarquements de sardines. La possibilité d'une corrélation entre les petits poissons pélagiques et l'énergie cinétique de l'AJ entrant n'est pas une hypothèse nouvelle. L'AJ à énergie cinétique élevée augmenterait la production primaire dans le nord de la mer d'Alberland, mais augmenterait également la dispersion des larves, ce qui aurait une incidence négative sur la survie des larves et le recrutement annuel d'anchois. Dans le sud de la mer d'Alboran, il y avait une relation positive entre la vitesse AJ et l'abondance des sardines, une vitesse plus élevée étant associée à une abondance plus élevée et vice versa.

Enfin, un quatrième profil de salinité était associé négativement aux débarquements de sardines. Toutefois, cette association ne peut être liée qu'à la variabilité interannuelle. Ce schéma de changement n'a pas montré de tendance globale significative, malgré une tendance positive de la salinité moyenne dans la région.

Outre les effets possibles des changements de température et de SLD à long terme sur le déclin des débarquements de sardines, le modèle linéaire choisi a pu reproduire les variations à long terme et interannuelles des débarquements de sardines et a expliqué 64 % de la variance des observations. Une deuxième possibilité envisagée dans ce travail consiste à supprimer la tendance linéaire des variables de réponse et de prédiction. Dans cette approche, une tendance linéaire est déterminée en ajustant une ligne droite à la série chronologique d'atterrissage, et les valeurs résiduelles représentent les variations annuelles liées au comportement linéaire. Cette approche ne permet pas d'expliquer le déclin à long terme des débarquements de sardines, et le modèle évalue l'impact des fluctuations annuelles des variables environnementales. Deux modèles possibles ont été obtenus : un modèle a établi une corrélation positive entre les résidus d'atterrissage et les concentrations de CHL-a avec un décalage d'un an (coefficient 1838 t mg de Chl-a^{-1} m^{-3}) et avec le SLD (coefficient 8 t mm^{-1}). Dans ce modèle, il existe également une corrélation positive entre l'atterrissage, la chlorophylle et le SLD et le premier modèle. Ainsi, les résultats de ces deux modèles suggèrent que l'augmentation des concentrations de Chl-a au cours de l'année précédant ou pendant l'année où les captures de sardines ont été enregistrées a eu un effet positif sur l'abondance des sardines. De plus, l'énergie cinétique de l'AJ entrant semble être un facteur important. Dans tous les cas, des résultats très similaires ont été obtenus, avec une augmentation/diminution d'environ huit tonnes pour chaque augmentation/diminution de 1 mm du SLD à travers le détroit. Lorsque les séries chronologiques des débarquements de sardines ont été reconstruites à l'aide de la tendance linéaire estimée et du modèle linéaire des valeurs résiduelles ou détendues.

Outre les variations à long terme et interannuelles des débarquements de sardines, les variations saisonnières ont également été mises en évidence par les débarquements moyens pour chaque mois de l'année calculés à l'aide de l'ensemble de la série chronologique. Ce cycle saisonnier indique les débarquements minimaux de février à avril. La température moyenne de la surface de la mer pour ces mois a également été calculée à partir des données satellites utilisées dans cette étude ; ces valeurs se situent entre 15,5 °C et 16,5 °C. Les maxima de débarquement ont été enregistrés d'octobre à janvier, ce qui montre une tendance récurrente claire des débarquements maximaux en automne, ce qui reflète probablement le réapprovisionnement en sardines qui s'effectue chaque année en septembre. La saison de reproduction des sardines se situant entre janvier et mars, on peut supposer que les débarquements minimaux correspondent à la saison de frai.

D'après les données disponibles, on peut suggérer que la saison de reproduction dans le sud de la mer d'Alboran est retardée par rapport à la côte atlantique voisine et au nord de la mer d'Alboran, ou simplement que les débarquements minimaux correspondent à quelques jours après le frai. Car la saison de recrutement (avec une probabilité de capture beaucoup plus élevée) aura lieu dans les prochains mois. Pour les anchois, à l'aide de séries chronologiques sur les tendances, les facteurs environnementaux expliquaient 60 % à 79 % de la variance totale des débarquements d'anchois, et la plupart des modèles obtenus étaient statistiquement significatifs. La température, la salinité et la composante du vent en U présentaient tous une association négative avec les débarquements d'anchois. En revanche, la vitesse des jets de l'Atlantique lorsqu'ils traversent le détroit de Gibraltar était en corrélation positive avec les atterrissages d'anchois.

Malheureusement, étant donné que la plupart des facteurs environnementaux et des débarquements d'anchois en Méditerranée ont montré des tendances claires, ce qui pourrait souligner les corrélations observées dans notre modèle. À l'aide de séries chronologiques ajustées aux tendances, aucune association entre la fréquence des anchois et les variables environnementales n'a été trouvée. Par conséquent, bien que les SST, SSS, U et V puissent être utilisés pour prédire l'abondance des anchois au cours des cycles saisonniers, ils ne peuvent pas prédire les tendances à long terme. Cela peut être dû à deux facteurs : les données environnementales ne montrent aucune tendance significative sur la période analysée (38 ans), et d'autres facteurs plus importants influents sur le déclin de l'abondance des anchois dans le sud de la mer d'Alboran, tels que la pression de pêche accrue sur les principales espèces ciblées.

Dans le cas du maquereau, sur la base de données originale, la salinité de la surface de la mer a été sélectionnée pour tous les modèles. Ce facteur est donc le principal moteur du maquereau de l'Atlantique dans cette région. En fait, le SSS reste le prédicteur le plus important après l'utilisation des séries chronologiques détendancielles. Une corrélation positive a été observée avec les débarquements de maquereaux, ce qui suggère que cette espèce préfère une salinité plus élevée et que les récentes augmentations de salinité dans la région ont eu un impact positif sur cette espèce.

Les adaptations physiologiques du maquereau pour supporter les variations de salinité sont probablement à l'origine des effets bénéfiques du SSS sur celui-ci. En particulier, le maquereau peut contrôler ses fluides corporels afin de maintenir l'équilibre osmotique dans des conditions de salinité variable et possède une tolérance élevée à l'eau salée. Par conséquent, l'élevage du SSS peut être avantageux pour cette population d'espèces. En fait, la salinité n'a aucun impact sur cette espèce, mais elle met en évidence un processus de fertilisation de l'eau plus complexe, car il était lié à une masse d'eau plus riche en nutriments pénétrant dans le golfe de Gascogne. Par exemple, une augmentation de la salinité dans notre région d'étude pourrait indiquer une plus grande intensité de remontée d'eau dans la mer d'Alboran.

Le deuxième prédicteur le plus courant dans les modèles était le débarquement d'anchois. Pour une raison ou une autre, cette autre petite espèce pélagique présentait une corrélation positive avec le maquereau à la fois dans la série chronologique originale et dans la série chronologique à tendance modifiée. Cette association positive n'a pas été observée car la capture de sardines n'a été sélectionnée dans aucun modèle significatif. Selon les résultats de notre étude, la capture d'anchois a également servi de prédicteur significatif. Cette conclusion peut s'expliquer par la possibilité que ces deux espèces coexistent dans le même habitat ou par la relation étroite entre leurs taux de capture respectifs. Comme ces deux espèces ne se disputent pas leurs proies, le maquereau pourrait s'en nourrir.

De plus, plusieurs études ont fait état d'une relation positive entre l'abondance de l'anchois et celle du maquereau, indiquant que ces deux espèces coexistent et partagent des niches écologiques similaires dans l'écosystème marin. En outre, on sait que le maquereau se nourrit d'anchois, mais l'aire d'alimentation du chinchard à grandes écailles comprend également des poissons appartenant à trois groupes écologiques. Les juvéniles d'espèces épipélagiques de masse telles que la sardinelle ronde, le chinchard de Cunene, l'anchois européen et le pilchard européen ont été inclus dans la première catégorie. Les espèces mésopélagiques des familles des Paralepididae et des Myctophidae constituaient le second groupe. Les espèces benthiques et marines constituent le troisième groupe. Les crustacés et le zooplancton constituent les principales sources de nourriture du méné à grandes écailles. La répartition et l'abondance du maquereau de l'Atlantique et de ses proies peuvent être influencées par un large éventail de conditions environnementales. En tant qu'espèce cible importante, il est important de comprendre les interactions physiques et trophiques qui déclenchent son abondance, et comment elle pourrait être affectée par différents scénarios de changement climatique.

Le SLD, qui représente le courant atlantique riche en nutriments et en Chl-a provenant du détroit de Gibraltar, semble être un autre facteur limitant pour le maquereau, car des niveaux plus élevés entraînent l'entrée d'un courant atlantique plus riche en nutriments dans la mer d'Alboran. Cela pourrait s'expliquer par l'effet fertilisant de l'AJ. Les jets de l'Atlantique qui déferlent sur la région ont un impact important sur les animaux résidant dans la mer d'Aboran, en particulier sur les petites espèces de poissons pélagiques. Ces jets puisent l'eau de l'Atlantique qui est fertilisée par les processus de mélange dans le détroit de Gibraltar, ce qui augmente la production primaire et, par conséquent, le nombre de petits poissons pélagiques.

La température de surface de la mer est le quatrième paramètre environnemental sélectionné. Il a été sélectionné en utilisant uniquement la série chronologique complète, et non l'ensemble de données de tendances supprimées. Ce facteur a également montré une association positive avec les espèces, mais n'a pas été pris en compte en raison de l'absence de tendances, ce qui suggère que l'effet de ce facteur sur les espèces ne s'est produit qu'à une échelle interannuelle (saisonnière). L'abondance et la dispersion du maquereau peuvent bénéficier de la hausse des températures. La fourchette de la température écologique du maquereau tend à se déplacer à mesure que les températures augmentent, offrant ainsi à l'espèce de meilleures conditions climatiques. Le réchauffement de l'océan provoqué par le changement climatique pourrait entraîner une augmentation du nombre du maquereau. Cela est vrai dans notre cas, car l'augmentation de la température de surface de la mer a montré une relation positive avec l'augmentation des débarquements pour cette espèce.

En revanche, les vents CHL-a et V ont été sélectionnés uniquement en utilisant les séries chronologiques désordonnées et présentent deux effets opposés. Des corrélations positives ont été observées chez le maquereau avec le vent en V, ce qui peut indiquer que les vents du nord ont un effet positif sur l'abondance du maquereau. Par conséquent, la vitesse et la direction du vent peuvent également avoir un impact considérable sur les petites espèces pélagiques. Les variations de la vitesse du vent peuvent affecter les courants océaniques, ce qui peut modifier la répartition des ressources alimentaires et le mouvement des larves et des œufs. Par exemple, l'augmentation de la vitesse du vent peut augmenter le mélange dans la colonne d'eau, ce qui réduit les concentrations de phytoplancton et la quantité de nourriture à laquelle les espèces de maquereau ont accès.

Selon nos résultats, il existe une association négative surprenante entre les composants ambiants CHL-a (indicateur de production primaire) et le débarquement de l'espèce. Ce composant a un coefficient de corrélation négatif et n'a été inclus que deux fois dans les modèles.

En conclusion, nous pouvons voir à quel point il est difficile de modéliser la réaction de ces petites espèces pélagiques aux changements environnementaux. En effet, il est également très difficile de prévoir avec précision comment le changement climatique affectera les petites espèces pélagiques en raison de l'absence de plans de surveillance à long terme établis, de la rareté des données, des changements environnementaux complexes et de la surpêche.

C'est pourquoi il est si important de mener d'autres études interdisciplinaires pour tenter de bien comprendre l'impact du changement environnemental et de la pêche sur le fonctionnement de l'écosystème en général, et sur la dynamique et la population des petites espèces pélagiques en particulier.

I. Chapter 1: General introduction

1. Introduction

1.1 Climate and environmental changes

Because of the consequences of large-scale, climatic and environmental changes and its impact on the distribution and abundance of fish populations, fishery scientists and managers have been particularly concerned with the evaluation and management of fisheries for many years. First, we should understand how it will evolve regarding green house emissions, and how these changes might influence the marine ecosystem and fish populations.

As the average weather conditions and their evolution over time at a certain overlaying atmosphere have a significant impact on atmospheric and meteorological conditions, the term "climate" was historically primarily used to refer to the near-surface atmospheric environment. The American Meteorological Society (AMS) defines climate as "the slowly varying aspects of the atmosphere-hydrosphere-land surface system" (Glickman, 2000). The average weather, or more precisely, the statistical description in terms of the mean and variability of the traditional period of 30 years, is how climate is typically characterized in a restricted sense. According to the World Meteorological Organization, the definition of marine climate, which adopts the IPCC's idea for the definition of climate, is the statistical description of maritime weather in terms of mean and variability (Humboldt, 1845; Koppen (1923); Bernstein et al. 2008; Solomon et al., 2007).

Climate changes that take place within the ranges of "natural" variability (such as El Nino, the Pacific Decadal Oscillation, and ice ages) have long been studied. On inter-annual to centennial time intervals, the climate has changed significantly and continually, according to long-term records from ice, tree rings, and sediment cores. There is evidence that climate through greenhouse gas emissions has resulted a global temperature warming (Joos et al. 2001; Steffen et al. 2005).

Global warming over the last century is both a problem and a challenge, and man-made changes in the environment are undeniable. Its potential climate impacts are substantial, but complex feedback loops within the climate system (all of which may not yet be known or even understood) prevented this warming from being attributable to human influence until the mid-1990s. Increases in greenhouse gas emissions are likely to continue. Assuming real global population growth over the next century, atmospheric concentrations will increase by 50% to 300% by 2100, across all estimates of annual CO2 emission rates. These estimates all assume that emission controls planned at the international level are at least partially met. Greenhouse gases that are harmful to the ozone layer will exacerbate the greenhouse effect. Pre-industrial CO2 levels may have effectively doubled by 2050, with contributions from gases other than water vapour. This will result in a further reduction in IR flux upwards of 1.5 Wm-2, supplementing the existing IR flux of 2.5 Wm-2. Thus, an escalation of the existing enhanced greenhouse effect leads to increase radiative forcing, thereby providing a mechanism for anthropogenic climate change over the next century. Earth's ecosystems have adapted to this change before, though perhaps not as quickly. However, human domination of the global environment is creating an unprecedented situation. The sheer size of our species, the political systems of our nation-states (whose populations have historically been bound by borders and identities), and the lack of clear international decision-making point to the potential for conflict in the future as climate boundaries change markedly and rapidly (Bigg, 2003; Steffen et al. 2005).

As the ocean and the atmosphere share a common boundary: the air–sea interface. This direct physical contact enables the two-exchange energy and matter. It is expected that the physical forcing of a warmer climate will lead to a number of significant changes that may directly affect ocean biological production. As a result, stratification in the surface layers can increase with a warmer surface ocean (e. g. McGowan et al., 2003). This would decrease the efficiency of wind induced mixing, reducing the input of nutrients into the euphotic layer and decreasing the productivity of the ocean. (Behrenfeld et al., 2005). Furthermore, it is not yet clear the evolution that the productivity of the oceans will have under a scenario of climate change as different processes could counter-balance. Snyder et al. (2003) projected an intensified upwelling season with some changes in seasonality to possibly counteract increases in sea surface temperature.

For instance, climate change can have an influence on ocean productivity by increasing acidification, which happens when the ocean absorbs carbon dioxide from the atmosphere. This process lowers the pH of the water, making it more acidic (Doney et al, 2020). Ocean acidification can cause changes in growth, development, abundance, and survival in marine species (Guinotte & Fabry 2008; Kroeker et al, 2019; Vézina et al, 2008). These changes have the potential to have a profound influence on the ocean's ecosystems, including a loss in the number of species and biodiversity. Another effect of climate change on ocean productivity is a reduction in phytoplankton production and disturbance of marine food networks. Key elements that drive marine ecosystems, such as winds, water temperatures, and sea ice cover, vary as the seas warm, resulting in changes in phytoplankton variety and evenness (Henson et al, 2021). A decrease in phytoplankton production can have an adverse effect on the productivity of bigger animals and commercial fisheries (Du Pontavice et al, 2021; Deppeler et al, 2017). The disturbance of the marine food chain has the potential to have far-reaching effects for both the ocean's ecosystems and the global economy. Rising water temperatures are also wreaking havoc on marine habitats. The warming ocean is having an impact on marine species at all trophic levels, causing changes in the location, distribution, and quantity of marine fisheries (Pörtner et al, 2019; Issifu et al, 2022).

Furthermore, growing atmospheric CO2 levels and climate change are linked to simultaneous changes in temperature, circulation, stratification, nutrient availability, and ocean chemistry (Doney et al, 2012). These changes can have far-reaching consequences for the ocean's ecosystems, including changes in marine species distribution and abundance, as well as harm to marine and coastal ecosystems. According to Auad et al. (2006) a 36% increase in atmospheric CO2 concentration causes increases in sea surface and near-surface temperatures and increases stratification along coasts. However, the predicted increase in stratification proved insufficient to overcome the effects of increased favorable upwelling, which predicted and resulted in a 30% increase in near-surface vertical velocity at the start of the upwelling season, as well as anomalies. Inshore transport in most coastal regions was shown to increase trophic concentration. Increased upwelling rates are projected to lead to more nutrient-rich waters in surface and near-surface oceans off the coast of California, where local ocean currents carry these nutrients.

More changes can be seen, as large-scale wind shifts discovers potentially significant changes in the large scale forcing of eastern boundary current forcing over the next century using an ensemble of linked climate model simulations. Peak-season equatorial wind force in upwelling-favorable eastern boundary winds should reduce, resulting in less upwelling, less phytoplankton productivity, warmer surface ocean temperatures, and less fog response in ocean circulation suggested by modeling studies. McGowan et al. (2003) anticipated worldwide changes in ocean physics that will likely result in higher temperatures and more stratification. While warming and light supply directly affect photosynthesis, increased vertical stratification and water column stability will reduce nutrient availability to the euphotic zone, assuming nutrient supply remains constant.

1.2 Climate variability and marine species

Climate change is projected to shift most terrestrial and marine species communities to the poles. This is because temperature is a key factor in the distribution of marine animals due to direct (e.g. metabolism, especially tolerance to planktonic larval stages) and indirect effects (e.g. substitution of other environmental conditions, predator-prey distribution) tolerance, (especially at the planktonic larval stage) manifested as latitudinal changes or habitat expansion/contraction, especially for mobile species such as fish. For exemple benthic species have their average latitude, depth, or both shifted). Over a 25-year period, in response to the recent enlargement of the North Sea margin, the frontier moved northward with warming, but differences in movement speed between species caused migratory species to move faster and have smaller life cycles. (Southward et al., 1995; Parmesan and Yohe, 2003; Beaugrand and Ibáñez, 2004).

For instance, climate change may also alter plankton and fish community structures. In fact, Boyd and Doney (2002) conclude that regional shifts are as important as changes in large-scale productivity. Seasonal shifts in biomass and dominant phytoplankton in the subarctic-subtropical transition were realted to global warming across all regions. These changes in phytoplankton may provide further or additional explanations for large-scale changes in zooplankton biogeography in many places in response to changes in climatic zones (Beaugrand et al., 2002).

For example, the Bering Sea has shown relevant changes since around 1990, leading to speculation as to whether the increase in jellyfish biomass was a result of human disturbance. However, peak levels of gelatinous zooplankton in the Bering Sea have declined significantly and have remained low since 2000 (King. 2005), so it is still unclear whether the blooms in the 1990s were related to long-term trends or isolated events. In the Bay of Biscay, many fish species live on the southern or northern boundaries of their ranges, and recent climate change has altered the structure of fish communities. In the negative trend group, one-third (seven) of the species were characterized by a northern distribution and a narrow latitudinal distribution. Another group of biomass consists mainly of transitional species with no long-term trend. All in all, many fish species are found at the southern or northern limits of their range, and recent climate change has resulted in changes in the fish community structure in this bay (Poulard and Blanchard, 2005).

The impact of further warming on commercial fisheries of cod, flounder, blue whiting or redfish is through continued distributional changes as well as changes in food webs. For example, different displacement rates may lead to changes in the spatial overlap between species, especially disrupting interactions. GLOBEC studies from 2003 to 2005 reported a sudden increase in warm-water pelagic species (Pilchardus) in the northwestern North Sea, suggesting that anchovies and sardines are now spawning in the southern North Sea. This increase would have more to do with the recovery of sardine populations near California than with allowing sardines to migrate to the North Sea related to the warmer waters(Voss et al. 2009). An example of a direct effect of temperature on recruitment is given by Planque and Frédou (1999), who studied cod recruitment in different regions of the ocean. In regions where temperatures are below optimum for cod, Drinkwater (2005) used predicted changes in the temperature field and known observed cod responses to temperature changes to estimate the response of North Atlantic cod stocks.

It is thought that some oceans could disappear by 2100 due to projected temperature changes, with areas of the southern North Sea and George Shoal receding. According to Drinkwater (2005), the response to future climate change is highly uncertain and depends on changes in other climate and ocean variables besides temperature, such as growth inducted by "the optimal growth temperature" hypothesis to explain the climate change to some small pelagic species regime shift (ex: sardine and anchovy). They suggest that this variation is caused by differences in the optimum temperature for growth rate early in life, with anchovies having a higher temperature optimum (22 °C) than sardines (16 °C). Between optimal temperatures, there may be fluctuations in the growth rates of the two species, and changes in the species' occurrence in the western North Pacific. Regardless of the underlying processes, further climate change is expected to correspondingly amplify these geographic differences in recruitment, leading to shifts in species distribution especially for some vulnerable key species such as small pelagic species.

1.3 Environmental changes and small pelagic fisheries

Small pelagic species are very important in commercial fisheries, making up 22% of global marine catches around the world (FAO, 2011).This is true for the Mediterranean and Black Sea where anchovies (393,500 tons/year) and sardines (186,100 tons/year) are the dominant species, accounting for 26% and 12% of the total catch (FAO, 2016). These species play a key role in marine ecosystems because of their high biomass and their role in linking lower and higher trophic levels (Bakun, 1996). Small pelagic fish with fast growth, early maturation, and few reproductive age classes are highly vulnerable to environmental changes due to their strong dependence on the sub-surface hydro-climatology and the spatial and temporal variability of primary production (Brosset et al., 2015, 2016, 2017; Hidalgo et al., 2011; Lloret et al., 2004).

Another factor affecting these species is the increasing fishing effort. Catches are experiencing negative trends suggesting a possible decline of the stocks (GFCM, 2016). Pinsky et al. (2011) demonstrated that the probability of these fisheries collapsing is similar to that observed for large body and late-maturity species. Climate change is recognized as another potential threat to exploited marine resources (FAO, 2008), with changes in sea temperature potentially altering the biology of marine species, their seasonal cycles, and their distribution.

These changes could have a higher impact on small-bodied and fast growing species, like small pelagic fish (Perry et al., 2005). Because of its reduced dimensions when compared with the world oceans, and its semi-enclosed character, the Mediterranean Sea could be particularly sensitive to climate change (Garcia- Martinez et al., 2018; Vargas-Yáñez et al., 2017; Bethoux et al., 1999).Tugores et al. (2011) showed the impact of environmental variables such as temperature, salinity, and chlorophyll concentration on sardine habitat suitability, and Raybaud et al. (2017) suggested that climate change could cause a moderate decrease in anchovy abundance during the 21st century. Brosset et al. (2017) found a decrease in anchovy and sardine body condition, but this could not be related to the main climatic indices. These authors suggested that regional environmental changes and their impact on phyto- and zooplanktonic assemblages could be linked to this body condition decrease through bottom up control mechanisms (Brosset et al., 2015, 2016). Sabatés et al. (2006, 2009) showed that sea water warming was responsible for the change in the distribution of Sardinella aurita which had extended northwards into the North Western Mediterranean Sea (Catalan shelf).

1.4 The importance of small pelagic in the Moroccan fisheries context

The Moroccan fishery catches more than 1.42 million tons of marine commercial species, and generates sales of more than 15 billion MAD, accounts for 2% of GDP, and employs approximately 360,000 people directly or indirectly (DPM, 2021). Historically, small pelagic species represent the bulk of Morocco's fisheries potential, accounting for 80% of fish production. Small pelagic resources mainly include clupeid species (*Sardina pilchardus*, *Sardinella aurita* and *Sardinella madarensis),* scombrids (*Scomber colias),* carangids (*Trachurus trachurus, Trachurus trecae* and *Trachurus mediterraneus*) and engraulids *(Engraulis encrasicolus*) (INRH, 201).

Small pelagic fisheries are divided into two categories: southern pelagic fisheries and northern pelagic fisheries. This southern fishery is operated by national and foreign fleets between Boujdour and Lagouira, in the southern regions of Morocco. The national fleet consists of RSW pelagic trawlers and coastal seiners. The foreign fleet operating under the fisheries agreement with the Kingdom of Morocco consists of pelagic freezer trawlers. The fishery targets sardines, mackerel, mackerel and pilchard, which are the main species of small pelagics in southern Morocco. This is an area rich in fish as the permanent upwelling that ensures the upwelling of deep cold waters rich in nutrients and nutrient. In 2019, the fishery produced more than 720,000 tonnes of small pelagic fish (DPM, 2021; INRH, 2019).

The northern pelagic fishery is an Atlantic and Mediterranean fishing activity with more than 600 costal purse seiners operating in 20 ports. The main ports in terms of activity and number of seiners are: Laayoune (194), Safi (59), Tan-Tan (55), Agadir (49), Larache (43) and Media Island (38) and Sidi Ifni (30) Nador (23), M'diq (21), Al Hoceima (18) and Ras Kabdana (15) distributed in the Atlantic and Mediterranean. This type of fishing takes place on the continental shelf, usually at depths of less than 100 metres. Purse seine vessels target small pelagic species, mainly sardines, anchovies and mackerel. In many areas, this fishery benefits from high biological productivity from upwelling (upwelling of cold, deep water), rich in nutrients that favors the presence of small pelagic species. In 2019, it was reported that this fishery produced 601,000 tonnes of small pelagics. 74 percent of this catch was caught in the ports of Laayoune (58 percent) and Tan Tan (16 percent) (DPM, 2021; INRH, 2019).

As fishing for small pelagic species is the main activity in the Mediterranean. This activity has decreased over the past two decades, leading to increased interactions between the top predators and seine vessels in the region. Bottlenose dolphin groups attacks fishing boats while circling pelagic fish such as sardines and anchovies, causing huge economic losses to fishermen and putting these protected species at high risk of injuries (Malouli et al., 2020).

While the decline in this small pelagic fisheries is thought to be primarily due to fishing, climate change and its impact on the disruption of the marine ecosystem may also have affected these species, especially since the Mediterranean Sea is a semi-enclosed and highly sensitive to environmental changes (Abdellaoui et al., 2017; MM Garcia et al., 2018).

In fact, the reasons for this decline have been largely debated by Moroccan fishermen, who claims that their activities are not the main cause of this decline, and that a great deal of research has been done on the evolution of these fish stocks, as well the fishing impacts (monitored annually by the INRH), but very few studies have attempted to understand the relationship between the dynamics of these species and changing oceanographic conditions in the region (Abdellaoui et al., 2017; Jghab et al., 2019; Vargas et al. et al., 2020; INRH, 2016).

II. Chapter 2: Methodology

2.1 Objectif of the reseach

The goal of this Ph. D. thesis is to test the influence of environmental variables such as Sea Surface Temperature, Salinity, Chl-a concentration, Sea Surface circulation, along with other oceanographic variables on both the long-term and inter-annual variability of small pelagic target species abundance in the southern Alborán Sea.

Using multiple linear regression models to identify the main environmental variables correlating with the abundance/ commercial catch of the most important pelagic target species (Anchovies, Sardine, and Makerel) at the southern Alborán Sea.

2.2 Study area

The Moroccan Mediterranean Coast

- **Geomorphological framework**

From Saidia to Cape Spartel (East to West), the Moroccan Mediterranean coastline appears as a succession of several elements in concave arcs towards the North. Generally rocky, steep, and inhospitable, the coastline sometimes drops down and is then bordered by sand dunes. It is a typical collapse coast extended by a narrow continental shelf, compared to the Atlantic shelf, although relatively wide here for a Mediterranean coast (J. Collignon 1965).

The shape and nature of the coasts and continental shelves play a very important role in the existence and development of marine resources, moreover the maritime depths are very irregular with a relatively wide platform on the eastern side and a very uneven bottom relief.

on the west side. Between Cap des Trois Fourches and Ceuta, the continental shelf itself is relatively narrow and often encumbered by rocks, especially around 100 m depth. The slope is comparatively gentle, with the distance between the 200 m and 600 m depths often exceeding 20 miles. However, the slope is not trawlable everywhere. There are significant rocky areas, such as Xauen and Tofino Banks. Observations made in 1959 mainly concern trawlable bottoms from 130 to 600 meters.1 (J. Collignon 1965; M Claude, 1962). (See figure below of the study area)

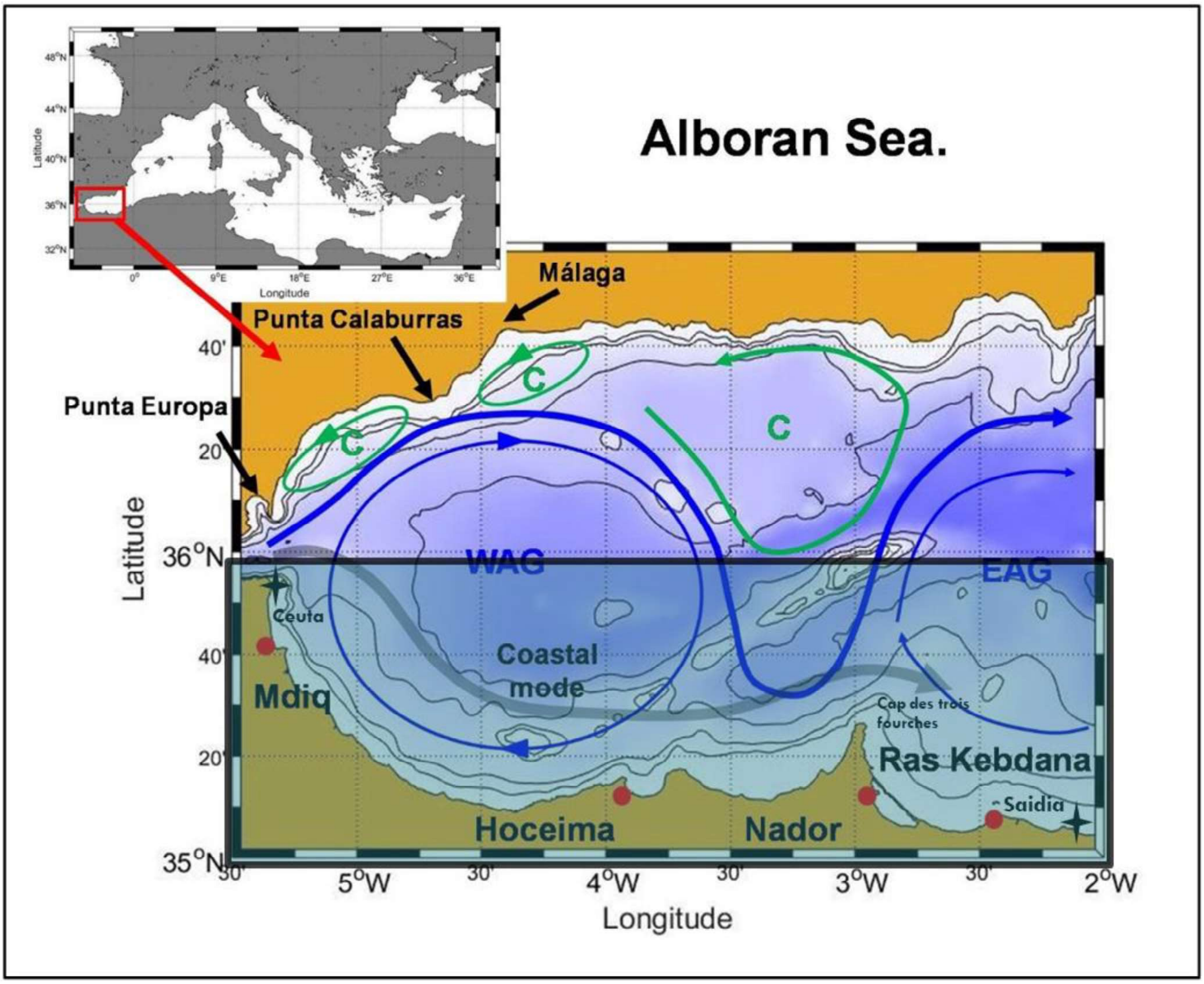


Figure 1: Map of the study Area (blue rectangle shows the designated study area; red dots indicate the locations of the main fishing harbors; black stars denote the boundaries or limits of the study area; blue and green rows represent oceanic circulations).

- **Hydro climatology**

The Mediterranean coast is characterized by a warm, temperate Mediterranean climate. Subtropical in character, it is characterized by two seasons, a cool, wet winter with often brutal precipitation, which extends from October to April, and a hot, dry summer that begins in May and lasts until the end of September (Stitou, 2002).

The direction and predominance of winds in northern Morocco are due to the topography of the Strait of Gibraltar. From May to October, there are moderately strong winds, mainly from the eastern "Chergi" and the western "Gharbi" sector from October to February. Finally, there is a constant balance between East North-East and West South-West winds from March to April (L.P.E.E., 1987).

Ocean circulation: The general circulation of an area such as the Mediterranean is, in most cases, the main factor governing circulation on the continental shelf and in coastal areas.

In the western part of this basin, general water circulation is guided by a flow entering through the Strait of Gibraltar, at the surface, from the Atlantic Ocean. It is represented by the superposition of two water masses, one Atlantic surface, with salinity of 36.15 g/l and temperature of 15 to 22°C, entering from west to east, at speeds of 40 to 60 cm/s (Lacombe & Richez, 1982), the other Mediterranean deep, with salinity of 38.4 g/l, temperature of 13°C and higher density, exiting from east to west at a speed of 30 cm/s (Lacombe et al., 1964; Frassetto, 1964). Thermohaline circulation is governed by the difference in density between Atlantic and Mediterranean waters and has a strong influence on the surrounding climate by modifying sea surface temperature (Somot et al., 2006). Part of the water then circles the basin, following the coast southwards, along North Africa, then northwards, generating a general cyclonic circulation (Landes & Crosnier, 2005). As it passes through the Mediterranean Sea, the Atlantic jet of water provokes two anticyclonic eddies, the variations and intensity of which are constantly monitored by satellites.

2.3 Data collection

Following the delimitation of the study area, data acquisition proceeded, encompassing the collection of two distinct datasets: fishing data and oceanographic data.

Data on the monthly small pelagic landings on the Mediterranean Moroccan coast from 1983 to 2020 were collected from the Moroccan National Fisheries office. Data were from the mean fishing ports: Mdiq, Al Hoceima, Nador, and Ras Kebdana, although some other, smaller ports also contribute to the total small pelagic landings in this area.

The main features of the surface circulation and the main cyclonic and anticyclonic areas are included. The fleet effort (fishing days) was only available from 2009 to 2020. Landings per Unit Effort (LPUE) for this period were estimated as landings in metric tons divided by the number of fishing days.

In addition to small pelagic landings, particullarily of the main target species: sardine (*Sardina pilchardus*), Anchovy (*Engraulis encrasicolus*), and Mackerel (*Scomber colias*), information on environmental variables that potentially impact sardine recruitment and abundance were obtained from various sources. These variables are sea surface temperature (SST), sea surface salinity (SSS), surface chlorophyll-a concentration (Chl-a), the west-east (u) and south-north (v) compo- nents of the wind, the North Atlantic Oscillation (NAO) index, the Mediterranean Oscillation Index (MOI), and the Western Mediterranean Oscillation index (WeMO). SST, SSS, and Chl-a data were averaged over the southern part of the Alboran Sea, from 5.5°W to 2°W and from 35°N to 36°N.

Daily sea surface temperature data from 1981 to 2017 were obtained from NOAA high-resolution SST data, from the NOAA/OAR/ ESRL PSD, Boulder, Colorado, USA web site at https://www.esrl.noaa. gov/psd/ (Reynolds et al., 2007). This data set has a 0.25° × 0.25° resolution. Daily salinity data from 1987 to 2020 were obtained from The Copernicus Marine Environment Monitoring Service (Simoncelli et al., 2014). This dataset has a 0.063° × 0.063° resolution. Daily Chlorophyll- A data were also obtained from the Copernicus website. These data have a spatial resolution of 1 km × 1 km and run from 1997 to 2020 (available from GOS-ISAC-CNR, Volpe et al., 2012). Daily wind data with a 2.5° × 2.5° resolution (u, west-east and v, south-north components) were obtained from NCEP Reanalysis, from the NOAA/OAR/

ESRL PSD, Boulder, Colorado, USA web site at https://www.esrl.noaa. gov/psd/ (Kalnay et al., 1996).

The AJ in the Gibraltar Strait was considered to be another environmental variable with the potential to impact small pelagic fish. However, long time series for this variable are not available. To overcome this limitation, and according to García-Lafuente et al. (1998) and Vargas-Yáñez et al. (2002), the AJ can be considered to be in geostrophic equilibrium with the cross-strait sea level difference according to:

$$u = g\Delta\xi/fL$$

where u is the along-strait component of the Atlantic flow velocity, g is the gravity acceleration (9.8 ms^{-2}), f is the Coriolis parameter at a la- titude of 36°N (8.5×10^{-5} s^{-1}), L is the cross-strait distance, and $\Delta\xi$ is the sea level difference between Ceuta and Algeciras. According to this expression, the Algeciras-Ceuta sea level difference can be considered a good indicator of the changes in the inflowing velocity. Monthly sea level time series for Algeciras and Ceuta were obtained from the tide gauge network of the Instituto Español de Oceanografía and Permanent Service for Mean Sea Level (www.psmsl.org). Monthly time series for the cross-strait sea level difference were constructed for 1981 to 2020. Finally, the main atmospheric circulation patterns in the North Atlantic and Mediterranean Sea can influence the productivity of Mediterranean waters, in addition to the distribution and abundance of plankton (García-Comas et al., 2011; Fernández de Puelles et al., 2007) and high trophic level organisms (Hidalgo et al., 2011, 2015). Winter (December to March) and annual NAO indices were obtained from the National Centre for Atmospheric Research (2017). The NAO index is defined as the normalized sea level pressure difference between the Azores and Iceland.

The Mediterranean Oscillation Index (MOI) is defined as the normalized sea level pressure difference between Gibraltar and Israel. MOI values were obtained from the Climate Research Unit, University of East Anglia. The Western Mediterranean Oscillation index is more local, and defined as the pressure difference between San Fernando, in the Gulf of Cádiz, Spain, and Padua, in northern Italy (Martín-Bide and López-Bustins, 2006). These data were obtained from the Climatology Group at Barcelona University (www.ub.edu/gc/en).

2.4 Data Analysis

The data analysis process is divided into two phases, a data preparation phase and a modeling phase, the first phase brings together the data collection part, calculation of operating indicators or called LPUE (Landing per Unit Effort), transformation 3d satellite data (longitude, latitude, and time) in time series and also the calculation of EOF or mode for environmental parameter indicators. Outlier detection and removal, normality testing, and then detrending.

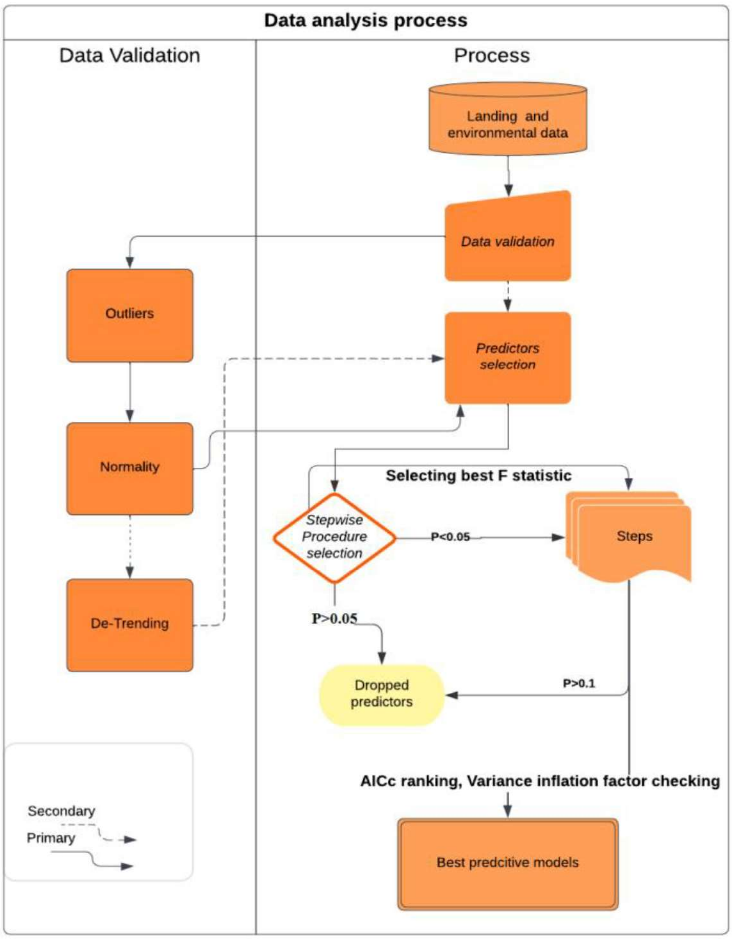
For the second phase, we apply step-by-step regression to select the factors, applying linear modeling. In each step we make a selection by the value F and we eliminate by the value p of the factor. I will explain better in the modeling part.

In phase the first phase, we started with the calculation of the LPUE (quantity caught/fishing effort or number of fishing days). Then we validated the data on the sum of catches in relation to the LPUE and as you see we have a very strong correlation so we can only use the quantities landed as indicators of the presence of these species at the fishing zone level. Ideally, LPUE are used as a proxy for species abundance, but we only have fishing effort data since 2009, which drastically reduces our data and does not allow us to carry out an environmental study.

Then, we did an analysis to detect outliers. And test normality using a distribution curve, and finally we made a first selection of variables by applying a cross-correlation between the variables and the species catches.

During the second phase, stepwise selection (forward selection) was applied. We have programmed a regression-based variable selection algorithm in R. The model starts with a (null) model with no variables.

The model starts with a (null) model with no variables. In each step, a regression is established by leaving a given year, the variables are ranked by F and P value, the predictor with the best F and with a P value less than 0.05 is selected. Next, another step is performed, but with the model based on the value already selected. Predictors can be discarded if their P-value is greater than 0.1. If the model fails to select any predictor with a P-value below 0.05, we stop the procedure. We then classify the models generated according to their AIC, R2 and P-value (see figure below).



Jghab et al, 2023

Figure 2: Data analysis procedure

Stepwise selection is an ascending method; we have programmed an algorithm for selecting variables by regression in R. The model starts with a (null) model without variables. In each step a regression is established leaving a year of data, the variables are classified by the F and P value, the predictor with the best F and with a P value less than 0.05 is selected. Afterwards, another step is carried out but with the base a model with the value already selected. Progressive predictors can be discarded if their P value is greater than 0.1. If the model cannot select any predictor with a P value less than 0.05, the procedure is stopped. Then we classify the models generated according to their AIC, R2 and P value.

III. Chapter 3: Results

The following chapter discuss the results of the study of the influence of the environmental factors and hydrodynamics on the main exploited small pelagic in the south Alboran Sea (Sardine, Anchovy, and Mackerel).

The results of this study are presented in a form of published scientific articles.

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The influence of environmental factors and hydrodynamics on sardine (*Sardina pilchardus*, Walbaum 1792) abundance in the southern Alboran Sea

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ABSTRACT

The study of environmental variables and their influence on the small pelagic fish stocks of the Alboran Sea (Western Mediterranean) is asymmetrical, with studies focused on the southern coast being scarce compared with those looking at the northern margin. In this work, time series of sardine landings from the Moroccan coast of the Alboran Sea from 1981 to 2016 were analyzed together with environmental variables such as Sea Surface Temperature (SST), Sea Surface Salinity (SSS), Surface Chlorophyll-a concentrations (Chl-a), and the velocity of the Atlantic Jet (AJ) flowing into the Mediterranean Sea through the Strait of Gibraltar. Annual sardine catches decreased from 1981 to 2016 at a rate of −258 t/year. At the same time, the SST and SSS increased at rates of 0.03 °C/year and 0.004 ups/year, respectively, very likely as a result of climate change. Linear models reflect a negative relationship between sardine landings and SST and SSS, indicating that the long-term temperature and salinity changes in the Mediterranean could have a negative impact on sardine abundance. At an inter-annual time scale, chlorophyll concentrations seem to be positively related to sardine abundances. A decrease in the kinetic energy of the AJ is also inferred from the cross-strait sea level difference (SLD). This variable has an important influence (positive correlation) on sardine landings, both in the long term and at the inter-annual time scale, with higher sardine abundances associated to higher SLD. This work shows that environmental variables such as SLD, SST, SSS, and Chl-a are the main driving factors for the variability of sardine landings in the southern Alboran Sea.

1. Introduction

Small pelagic species are very important in commercial fisheries, making up 22% of global marine catches around the world (FAO, 2011).This is true for the Mediterranean and Black Sea where anchovies (393,500 tons/year) and sardines (186,100 tons/year) are the dominant species, accounting for 26% and 12% of the total catch (FAO, 2016). These species play a key role in marine ecosystems because of their high biomass and their role in linking lower and higher trophic levels (Bakun, 1996). Small pelagic fish with fast growth, early maturation, and few reproductive age classes are highly vulnerable to environmental changes due to their strong dependence on the sub-surface hydro-climatology and the spatial and temporal variability of primary production (Brosset et al., 2015, 2016, 2017; Hidalgo et al., 2011; Lloret et al., 2004). Another factor affecting these species is the increasing fishing effort. Catches are experiencing negative trends suggesting a possible decline of the stocks (GFCM, 2016). Pinsky et al. (2011) demonstrated that the probability of these fisheries collapsing is similar to that observed for large body and late-maturity species.

Climate change is recognized as another potential threat to exploited marine resources (FAO, 2008), with changes in sea temperature potentially altering the biology of marine species, their seasonal cycles, and their distribution. These changes could have a higher impact on small-bodied and fast-growing species, like small pelagic fish (Perry et al., 2005). Because of its reduced dimensions when compared with the world oceans, and its semi-enclosed character, the Mediterranean Sea could be particularly sensitive to climate change (Garcia-Martinez et al., 2018; Vargas-Yáñez et al., 2017; Bethoux et al., 1999).

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Relationship Between Environmental Factors Changes and Anchovy Landing (*Engraulis encrasicolus*) in the South Alboran Sea

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ABSTRACT

In the Mediterranean, one of the most prized small pelagic species is the European anchovy (*Engraulis encrasicolus*). This species has long been targeted by fishermen in the southern Alboran Sea and the Mediterranean Sea. The objective of this research was to identify any linkages that may exist between environmental changes in the southern Alboran Sea and the reported drop in anchovy landings between 1983 and 2020. The method of forward stepwise regression was used, taking into account environmental indicators, such as sea surface salinity (SSS), sea surface temperature (SST), surface chlorophyll a (Chl-a), U and V wind components, NAO index, and Atlantic jet velocity. To select the best prediction models, generalized linear models (GLMs) were created and organized based on their corrected akaike information criteria (AICc) values. Trended time data were used to create six top models, which explained 60 to 79% of the variation in anchovy landings. Temperature, salinity, and the U wind component all displayed a negative association with anchovy landings. On the other hand, the Atlantic jets' velocity as they traveled through the Strait of Gibraltar was positively correlated with anchovy landings. When the trend component was taken out; however, none of the environmental variables could explain the variations in anchovy landings. This may imply that while environmental influences have an effect over the long term, they have little effect on the inter-annual time scale. Hence, the decline in landings of this species may be due to factors other than environmental change. Overfishing may have played a substantial role in the long-term decline in landings since this species was the most targeted of the small pelagic species in the study area.

INTRODUCTION

The Mediterranean is known for its heavily populated coastal regions, which result in high levels of human pressure, especially extractive fishing. The effects of various human pressures on the environment, ecosystems, and living resources of the Mediterranean Sea,

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Environmental Factors Changes and Its Association with the Catches Fluctuations of Atlantic Chub Mackerel (*Scomber colias*, Gmelin, 1789) in the South Alboran Sea (Western Mediterranean Sea)

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ABSTRACT

Based on data from 37 years of catches and environmental satellites in addition to model observations from 1983 to 2020, this study assessed the potential impact of changing oceanographic conditions on the Atlantic chub mackerel (*Scomber colias*) population in the southern Alboran Sea. To determine the best potential predictors, as well as building the best models to explain the variation of this species's abundance, forward stepwise regression was applied to environmental predictors, viz. sea surface salinity (SSS), sea surface temperature (SST), surface chlorophyll a (Chl-a), U and V wind components, NAO index, and the velocity of Atlantic jets represented by sea level difference (SLD). Then, linear models (LMs) were built and ranked by their AICc values to choose the best predictive models. The findings demonstrate that this species was vulnerable to a variety of environmental conditions, such as variations in sea salinity, temperature, currents, and wind patterns, which can affect both the species' abundance and how it was exploited by fisheries. This study emphasized the enormous impact of the Atlantic jet on the dynamics of small pelagic fish populations in the Alboran Sea, underscoring the need of taking oceanographic processes into account while managing these resources. However, it can be challenging to foresee how small pelagic species will be impacted by climate change due to the lack of long-term monitoring programs, data sources, and the complexity of environmental changes. Therefore, future research should be prioritized to better understand how environmental changes affect these species and their habitats.

INTRODUCTION

Small pelagic fish species play a vital role in marine ecosystems and are a critical food source for larger predatory species and human populations (**Tacon *et al.*, 2013**). However, the negative impact of climate change and associated environmental changes

IV. Chapter 4: General discussion

4.1 Environmental factors change in the south Alboran Sea

Analysis of sea surface temperature and salinity time series in the southern Alboran Sea showed that surface temperature and salinity increased significantly at rates of 0.03 °C yr^{-1} and 0.004 yr^{-1}, respectively. This is not surprising, as several studies have shown that the Mediterranean Sea has been experiencing warming and increased salinity since the mid-20th century, most likely driven by global climate change (Garcia-Martinez et al., 2018; Vargas-Yáñez et al., 2017; Skliris et al., 2012; Nicoyar, 2009). Although it was hypothesized that a warmer and more stable water column might reduce primary production (Polovina et al., 2008)), this effect was not observed in the Alboran Sea, at least for the period analyzed in this study(see also Vargas-Yáñez et al., 2022). Chl-a concentration increased at a rate of 0.005 mg $\text{m}^{-3}\text{yr}^{-1}$. Two possible explanations for this trend are proposed. On the one hand, while the upper layers have warmed, increasing the stability of the water column, on the other hand, salinity has also increased, which has the opposite effect. Changes in temperature and salinity can offset and prevent the decline in primary production associated with a more stable water column. On the other hand, primary production in the Alboran Sea may not be highly dependent on winter mixing, which would normally be suppressed by more stratification of the upper water column. In fact, the high primary productivity in the Alboran Sea may be related to other mechanisms, such as internal tidal mixing in the Strait of Gibraltar (Echevarría et al., 2002) or frontal and cyclonic circulation in the northern Alboran Sea (Sarhan et al., 2000, Reul et al., 2002, 2005). This nutrient- and chlorophyll-rich water would be carried southwards by the AJ around the Alboran Sea anticyclonic circulation (Oguz et al., 2014; Garcia-Gorriz and Carr, 2001; Ruiz et al., 2001), affecting positively the prey availability for sardine larvae and adults. Interestingly, there is a strong and significant negative trend in cross-strait SLD. One might assume that this variable is directly proportional to the velocity of inflowing water into the Mediterranean Sea (Vargas-Yáñez et al., 2002; García-Lafuente et al., 1998), which in turn, might be related to the direction of the AJ within the Alboran-Sea. Changes in the velocity and direction of the AJ would be related to different modes of circulation: Anticyclonic circulation mode, or coastal mode circulation. In the latter case, the AJ flows close to the Marroco coast after exiting the Strait of Gibraltar. (Bormans and Garrett, 1989; Vargas-Yáñez et al., 2002). The decrease in AJ velocity is likely due to an increase in air pressure in the western Mediterranean (Candela et al., 1989). This trend is the result of a reduced pressure differential between the Gulf of Cadiz and northern

Italy, which hinders AJ access through the Strait of Gibraltar and reduces SLD across the strait in the region. Another possibility for a negative trend in SLD across the Channel is weakening Atlantic-Mediterranean water exchange. This may be due to warming of the Mediterranean Sea and reduced formation of deep water in this sea. However, increasing salinity in the Mediterranean will offset the temperature effect. Currently, we are not aware of any work that demonstrates such a weakening of the Atlantic-Mediterranean water transports, and analyzing this issue is beyond the scope of this study.

4.2 Environmental factors changes and possible impact on small pelagics

Changes in environmental conditions can affect adult body condition and recruitment success, and these changes are particularly important for small, fast-growing and early-maturing species such as sardines, anchovies and meckerel (Brosset et al., 2017; Tugores et al., 2011; Hidalgo et al., 2011; Perry et al., 2005). As mentioned earlier, temperature is a key factor in spawning timing and will change as surface water warms. Therefore, there may be a mismatch between egg laying and other factors that affect larval survival, such as primary production. In addition, ocean warming increases stratification of the water column, reduces nutrient injection into the euphotic zone, and reduces primary production and prey availability for larvae and adults. Salinity is not expected to directly affect adult status, larval survival, or recruitment success. Nonetheless, it is an indirect indicator of the presence of fronts and upwelling areas within the Alboran Sea that have been shown to increase primary production east of Gibraltar and at the northwestern Alboran Sea (Reul et al. 2002, 2005). The other factors mentioned earlier (wind speed and direction (u,v), SLD, Chl a, SST, SSS) may also influence the distribution and recruitment of these species, especially since they show significant long-term trends in our study area.

Leaving aside possible reasons for the observed long-term trends, there appears to be a link between these changes and a decline in sardine and anchovy catches with positive effects that we will discuss in the following sections.

As sardine, anchovy and mackerel landings showed significant trends over the period of study, as did certain environmental factors, we applied the parameters and model selection process to original and trend-adjusted data and analyzed/compared the relationship on an inter-annual and intra-annual scale.

4.2.1 Sardine

If the trends are not removed from the sardine landing and environmental time series, the best-chosen linear model relates sardine landing to the previous year's SST, fourth salinity pattern (from Principal Component Analysis), and SLD in the same year as landing (with no time delay). It is also worth emphasizing that there is a negative relationship between landings and SST. One might argue that positive warming trends are partly responsible for the downward trend in sardine landings. The relationship between landings and SLD could indicate that a negative trend in SLD induces a negative trend in sardine landings. The possibility of a correlation between the small pelagic fish and the kinetic energy of the inflowing AJ is not a new hypothesis. Ruiz et al. (2013) suggested that an AJ with high kinetic energy would increase primary production in the northern Alberland Sea, but also increases larval dispersion, which would negatively affect larval survival and annual anchovy recruitment. In the southern Alboran Sea, there was a positive relationship between AJ velocity and sardine abundance, with higher velocity associated with higher abundance and vice versa. This behavior is opposite to that reported by Ruiz et al. (2013) for the Northern sector of the Alboran Sea. The explanation may be that AJ did not directly hit the coast south of Alboran, but orbited around the anticyclone west of Alboran, so the impact of high kinetic energy on larval dispersion was significantly reduced. In contrast, high AJ velocities are associated with higher chlorophyll concentrations in northern regions, eventually moving southwards through the AJ (Oguz et al., 2014; Garcia Gorriz and Carr, 2001), and possibly favouring the fertilization of the southern Alboran Sea waters. Finally, a fourth salinity pattern was negatively associated with sardine landings. However, this association can only be related to inter-annual variability. This pattern of change did not show a significant overall trend, despite a positive trend in mean salinity across the region. In addition to the possible effects of long-term temperature and SLD changes on the decline in sardine landings, the chosen linear model was able to reproduce the long-term and inter-annual variations in sardine landings and explained 64% of the variance of the observations.

A second possibility considered in this work is to remove the linear trend from the response and predictor variables. In this approach, a linear trend is determined by fitting a straight line to the landing time series, and the residuals represent annual changes around the linear behavior. This approach cannot explain the long-term decline in sardine landings, and the model assesses the impact of annual fluctuations in environmental variables. Two possible models were obtained:

One model positively correlated landing residuals with Chl-a concentrations with a time lag of one year (coefficient 1838 t mg Chl-a^{-1} m^{-3}) and with SLD (coefficient 8 t mm^{-1}). In this model, there is also a positive correlation between landing, chlorophyll and SLD and the first model. Thus, the results of these two models suggest that increased Chl-a concentrations in the year preceding or during the year when sardine catches were recorded positively affected sardine abundance. Also, the kinetic energy of the incoming AJ seems to be an important factor. In all the cases, very similar results were obtained, with an increase/decrease of about eight tons for every 1 mm increase/decrease of SLD across the strait. When the time series of sardine landings were reconstructed using the estimated linear trend and the linear model of the residuals or de-trended time series, the explained variance was 50% and 60% for Model 2 and Model 3, respectively. The positive effect of increasing Chl-a concentration on landings and successful anchovy recruitment has been reported for the Northern Alboran Sea (Ruiz et al.2013). Other authors have demonstrated the fact that sardine larvae prey on phytoplankton and micro zooplankton. Therefore, Chl-a-rich waters favor the survival of sardine larvae (Morote et al., 2010; Palomera et al., 2007). This not only affects sardines, but is also consistent with the strong survival dependence of juvenile hake species on annual Chl-a changes (Hidalgo et al., in press). In addition to long-term and inter-annual variations in sardine landings, seasonal variations were also evidenced by average landings for each month of the year calculated using the entire time series. This seasonal cycle shows minimum landings from February to April period. The average Sea surface temperature for these months was also calculated from the satellite data used in this study; these values are between 15.5 °C and 16.5 °C. Landing maxima were recorded from October to January, showing a clear recurring pattern of maximum landings in autumn, which likely reflects sardine replenishment that is completed each September (Tugores et al., 2011). As the breeding season for sardines is between January and March it can be assumed that the minimum landings correspond to the spawning season (INRH, 2015). However, the temperature range shown in these data is slightly higher than that reported by Bernal et al. (2007) who assumed that spawning would occur when the surface temperature was between 13.5 °C and 15 °C. The minimum landings also appear to be later than the maximum somatic gonadal indices found by Abad and Giráldez (1993) in the northern Alboran Sea. These authors reported peaks in December and January. From the available data it can be concluded that the breeding season in the southern Alboran Sea is delayed compared to the nearby Atlantic coast and the northern Alboran Sea, or simply that the minimum landings correspond to a few days after spawning. As the recruitement season (with much more higher probability of catches) will happen in the following next months.

In conclusion, long-term landings of sardines in the study area have decreased significantly from 1981 to 2016. The linear model reflects the possible effects of warming in the Alboran Sea (related to climate change for sure) and reduced AJ kinetic energy on the observed trend of decreasing sardine landings. Anticipated climate change impacts include increased water column stratification and reduced winter mixing, thereby reducing nutrient injection into the photic zone and reducing the intensity of winter/spring phytoplankton blooms. So far, these changes have not been observed in the Alboran Sea, and the Chl-a time series show a positive trend. One possible explanation for this is that the effect of ocean warming on the stratification of the Mediterranean water column may be offset by an opposite effect associated with increased salinity. Another possibility is that the Alboran Sea is influenced by specific upwelling mechanisms, such as frontal structures and cyclonic circulation areas. Chl-a concentrations in surface waters appear to be an important factor regulating the variability in annual sardine landings. Finally, for long-term and inter-annual variability, the linear model was able to explain approximately 60% of the variance in landing.

4.2.2 Anchovy

Using trended time series, environmental factors explained 60% to 79% of the total variance in anchovy landings, and most of the resulting models were statistically significant. Temperature, salinity, and the U wind component all displayed a negative association with anchovy landings. On the other hand, the Atlantic Jets' velocity as it travels through the Strait of Gibraltar was positively correlated with anchovy landings.

Unfortunately, since most environmental factors and anchovy landings in the Mediterranean have shown clear trends, which may underscore the correlations observed in our model. Using trend-adjusted time series, no association between anchovy frequency and environmental variables was found. Therefore, while SST, SSS, U, and V can be used to predict anchovy abundance along seasonal cycles, they cannot predict long-term trends. This may be due to two factors: the environmental data show no significant trend over the period analyzed (38 years), and there are other, more important factors affecting the decline in anchovy abundance in the southern Alboran Sea, such as the increased fishing pressure on the most important targeted species. On the other hand, Baez et al. (2022) showed that the combined effects of multiple regional and global climate changes provided the best explanation for the variation in anchovy and sardine abundance in (Spanish cost between cape of Palos and Barcelona).

4.2.3 Mackerel

Upon using original data, sea surface salinity was selected for all models; accordingly this factor is the most important driver of Atlantic mackerel in this region. In fact, SSS remains the most important predictor after using the de-trended time series. There was a positive correlation with mackerel landings, suggesting that this species prefers higher salinity, and that recent salinity increases in the region had a positive impact on this species. In fact, changes in SSS can have an impact on the species' distribution and abundance even though it is known to live in waters with a wide range of salinity levels (Radlinski et al. 2013). Our finding coincides with Lui et al. (2023) describing that higher SSS was linked to greater mackerel biomass and abundance in the eastern North Atlantic. Mackerel's physiological adaptations to endure salinity variations are probably what contribute to the SSS's beneficial effects on it. In particular, A. mackerel can control its bodily fluids to maintain osmotic balance in varying salinities and has a high tolerance for saltwater (ICES. 2021). As a result, raising SSS may be advantageous for this specie population. In contrast, other studies found that declining populations of mackerel have been associated with extreme increase in sea salinity in some areas such as the case for Wang et al. (2016). Nevertheless, Doray et al. (2018) research demonstrated a correlation between low salinity rich nutrient waters in the Bay of Biscay and enhanced mackerel biomass. As a matter of facts, salinity doesn’t impact this specie, but it does highlight a more complex water fertilization process, as it was linked with more rich nutrient water mass entering the Bay of Biscay. For instance, a salinity increase in our study region could indicate a higher intensity of upwelling in the Alboran Sea.

The second most common predictor in the models was anchovy landings. For some reason, this other small pelagic species was positively correlated with mackerel in both the original time series and the de-trended time series. This positive association was not observed as sardine catch was not selected in any significant model. According to the results of our study, anchovy catch also served as a significant predictor. This conclusion can be explained by the possibility that these two species coexist in the same habitat or by the close relationship between their respective catch rates. As these two species do not compete for prey, and chub mackerel could feed on this specie.

Over and above that, several studies have reported a positive relationship between anchovy and mackerel abundance, indicating that these two species co-occur and share similar ecological niches in the marine ecosystem. For instance, Bernal et al. (2019) found a strong positive correlation between anchovy and mackerel abundance in the Eastern Pacific Ocean. Similarly, Zhang et al. (2022) observed a positive relationship between the Spanish mackerel and Japanese anchovy in the Yellow Sea. They discovered that the presence of anchovy eggs may have a positive impact on mackerel spawning than environmental factors, indicating the importance of prey for predator's relationship between the two species during the early recruitment phase. According to Collette and Nauen. (1983), Castro et al. (1995), Domanevskii and Patokina. (1988), fish, zooplankton, and cephalopod mollusks are all part of the Atlantic chub mackerel's varied diet. The feeding range of Atlantic chub mackerel includes fish from three ecological groups, according to study by Gushchin et al. 2017. Juveniles of mass epipelagic species such round sardinella, Cunene horse mackerel, European anchovy, and European pilchard were included in the first category. Mesopelagic species from the Paralepididae and Myctophidae families made up the second group. Benthic and bottom species are the third group. Crustaceans and zooplankton have been the secondary food sources for the Atlantic Chub. The distribution and abundance of Atlantic mackerel and its prey can be influenced by a wide range of environmental conditions. As important target species it is important to understand the physical and trophic interactions that triggers its abundance and how A. mackerel abundance might be affected by different climate change scenarios.

SLD, which represents the nutrient and Chl-a rich Atlantic current from the Strait of Gibraltar, appears to be another limiting factor for mackerel, as higher levels lead to more nutrient-rich Atlantic current entering the Alboran Sea. This could be explained by the fertilization effect of AJ. The Atlantic jets flowing into the region have a substantial impact on animals residing in the Aboran Sea, especially small pelagic fish species. These jets draw water from the Atlantic that is fertilized because of mixing processes within the Strait of Gibraltar (Echevarría et al., 2002), increasing primary production and, in turn, the number of small pelagic fish. Huertas et al. (2012) found a correlation between the Atlantic Jet index and the quantity of sardines and anchovies in the Alboran Sea. Ruiz et al. (2013) indicated that the flow of Atlantic water into the Alboran Sea had a considerable favorable impact on the spawning success and recruitment of anchovy, which further substantiated the positive impact. This was demonstrated also in the south Alboran Sea, where the abundance of sardine, anchovy, and in our instance, A. mackerel was positively related with incoming nutrient tich AJ (Jghab et al., 2019; Jghab et al., 2023).

Sea surface temperature is the fourth environmental parameter selected. It was selected using only the full time series, not the de-trended dataset. This factor also showed a positive association with species, but was ignored due to the de-trended data, suggesting that the effect of this factor on the species only occurred on an inter-annual (seasonal) scale. Mackerel abundance and dispersion may benefit from rising temperatures. The ecological temperature range of Mackerel tends to move more northward as temperatures rise, presenting the species with better climatic conditions. According to a study by Jansen et al. (2016), the abundance and biomass of this specie considerably increased in the Greenland waters with rising sea surface temperature (SST). Agnalt (1989) showed in that mackerel grew and matured more favorably when temperatures rose within the optimum window. These findings imply that ocean warming brought on by climate change may result in a possible rise of A. mackerel. This is true in our case as the increase of increase of the sea surface temperature showed a positive relationship with increase of landing for this specie. Nevertheless, in other studies seems that this factor could also have a negative impact. Watanabe et al. (2010) found that variations in sea surface temperature can still affect the species' distribution and migration habits. For instance, changes in the distribution and movement of this Atlantic Mackerel have been related in some places to rising sea surface temperatures, which has resulted in population decreases in some areas (Kim et al. 2021).

On the other hand, Chl-a and V wind are selected using only the de-trended time series and show two opposite effects. Positive correlations were observed in mackerel with V wind, which may indicate that northerly winds have a positive effect on mackerel abundance. Hence, the wind speed and direction can also have a considerable impact on small pelagic species. Changes in wind speed may affect ocean currents, which may alter the distribution of food resources and the movement of larvae and eggs. For instance, increasing wind speed can increase water column mixing, which reduces phytoplankton concentrations and the amount of food that Mackerel specie has access to (Ogawa et al. 2011). The direction and speed of wind can also have a positive effect. Small pelagic species spread, and abundance can benefit from favorable wind, such as the relation observed between the northward wind and the landing of A. mackerel specie in our study area. This can be explained by the fact that westerlies (+U) can cause upwelling episodes (Sarhan et al., 2000, Reul et al., 2005), which raise primary productivity and transport more saline and nutrient-rich water to the surface, increasing the amount of food that small pelagic organisms have access to. Numerous regions, including the Canary Current in the Atlantic Ocean and the central Mediterranean Sea (Bignami et al. 2017), have shown a similar impact as increased wind intensity and frequency can result in an increase in the biomass of small pelagic species like anchovy (Engraulis encrasicolus) and sardine (Sardina pilchardus).

According to our findings, there is a surprising negative association between the ambient components Chl-a (primary production indicator) and the specie landing. This component has a negative correlation coefficient and was only included twice in the models. However, Kim et al. (2022) have demonstrated a beneficial relationship between Atlantic mackerel primary production. Since there aren't many studies on mackerel, we can compare these findings to some studies on the well-known small pelagic species (sardine) in the Mediterranean. In the case of this other species, Abdelaoui et al. (2017) discovered that there is generally little correlation between the abundance of sardine specie and chlorophyll in the western part of the south Alboran sea, a limiting concentration of less than 0.46 g/l (was reported despite of a favorable temperature (19°C). On the other hand, Jghab et al. (2019) found that landing residuals for the sardine were positively correlated with the Chl-a concentration with a one-year time lag.

V. General conclusion

English

Long term landings data of small pelagic species (sardines, anchovies, and mackerel) from 1983 to 2020 resulted in major changes in the southern Alboran Sea. While the impact of increased fishing pressure should be considered in future work, the current lack of fishing effort data does not allow any analysis on this issue.

The linear model reflects the possible effects of warming in the Alboran Sea (possibly related to climate change) and reduced AJ kinetic energy on the observed trend of decreasing sardine landings. Anticipated climate change impacts include increased water column stratification and reduced winter mixing, thereby reducing nutrient injection into the photic zone and reducing the intensity of winter/spring phytoplankton blooms. So far, these changes have not been observed in the Alboran Sea, and the chlorophyll time series show a positive trend. One possible explanation for this is that the effect of ocean warming on the stratification of the Mediterranean water column may be offset by an opposite effect associated with increased salinity. Another possibility is that the Alboran Sea is influenced by specific upwelling mechanisms. Chlorophyll concentrations in surface waters appear to be an important factor regulating the variability in annual sardine landings. Finally, for long-term and inter-annual variation, the linear model was able to explain approximately 60% of the variance in landing.

On the other hand, when modeling the time trend data, it was found that anchovy landings varied significantly. SST, SSS and U-wind are the main environmental factors affecting the abundance of anchovies. However, environmental factors could not explain the variation in anchovy landings after removal of the trend component. This may indicate that environmental factors, while having long-term effects, have little effect on inter-annual timescales.

As for the possible effects of environmental changes on Atlantic chub mackerel. The results suggest that this specie may be more sensitive to salinity, temperature, ocean current and wind patterns, and anchovy (prey) abundance, and that changes in these variables may affect their abundance and ultimately fishing exploitation. These results demonstrate the need to consider the impact of oceanographic processes when managing these fishery resources and suggest that the dynamics of these pelagic fish populations in the Alboran Sea are significantly influenced by the inflowing Atlantic currents.

It also notes how difficult it is to predict how climate change will affect small pelagic species due to the lack of established long-term monitoring plans, scarce data and complex environmental changes. The impact of environmental change on ecosystem functioning in general, and on small pelagic species in particular, requires further study in the future.

Management and conservation of small pelagic species requires a better understanding of how climate change and other factors are affecting these species. Multidisciplinary and basin-wide research and modeling, with links to northern and southern databases, is needed to improve our understanding of the impacts of climate change on these species and the ecosystems that support them.

In conclusion, small pelagic species are important components of marine ecosystems and important food sources for humans and large predators. Understanding and managing the impact of climate change and other impacts on these species is critical to ensuring their long-term survival and advancing sustainable management and conservation efforts. At the same time, factors other than environmental changes may also be responsible for the decline in landings of this species. As this species is the most commercialized small pelagic species in the study area, overfishing of this species may be a possible factor contributing to the long-term decline in landings.

Spanish

Los datos de desembarques a largo plazo de los pequeños pelágicos (sardinas, anchoas y caballa) de 1983 a 2020 provocaron cambios importantes en el sur del mar de Alborán. Si bien el impacto del aumento de la presión pesquera debe considerarse en trabajos futuros, la falta actual de datos sobre el esfuerzo pesquero no permite ningún análisis sobre este tema.

El modelo lineal refleja los posibles efectos del calentamiento en el mar de Alborán (posiblemente relacionados con el cambio climático) y la reducción de la energía cinética de los AJ en la tendencia observada de disminución de los desembarques de sardinas. Los impactos previstos del cambio climático incluyen una mayor estratificación de la columna de agua y una reducción de la mezcla invernal, lo que reduce la inyección de nutrientes en la zona fótica y reduce la intensidad de las floraciones de fitoplancton en invierno/primavera. Hasta el momento, estos cambios no se han observado en el mar de Alborán, y las series temporales de la clorofila muestran una tendencia positiva. Una posible explicación de esto es que el efecto del calentamiento de los océanos en la estratificación de la columna de agua del Mediterráneo puede compensarse con un efecto opuesto asociado con el aumento de la salinidad.. Otra posibilidad es que el mar de Alborán esté influenciado por mecanismos de surgencia específicos.. Las concentraciones de clorofila en las aguas superficiales parecen ser un factor importante que regula la variabilidad de los desembarques anuales de sardinas. Por último, para la variación a largo plazo e interanual, el modelo lineal pudo explicar aproximadamente el 60% de la varianza en el aterrizaje.

Por otro lado, al modelar los datos de la tendencia temporal, se encontró que los desembarques de anchoveta variaban significativamente. La SST, la SSS y el viento en U son los principales factores ambientales que afectan a la abundancia de anchoas. Sin embargo, los factores ambientales no pudieron explicar la variación en los desembarques de anchoas tras la eliminación del componente de tendencia. Esto puede indicar que los factores ambientales, si bien tienen efectos a largo plazo, tienen poco efecto en los plazos interanuales.

En cuanto a los posibles efectos de los cambios ambientales en el jurel atlántico. Los resultados sugieren que esta especie puede ser más sensible a la salinidad, la temperatura, las corrientes oceánicas y los patrones de viento, y a la abundancia de anchoas (presas), y que los cambios en estas variables pueden afectar su abundancia y, en última instancia, la explotación pesquera.. Estos resultados demuestran la necesidad de considerar el impacto de los procesos oceanográficos en la gestión de estos recursos pesqueros y sugieren que la dinámica de estas poblaciones de peces pelágicos en el mar de Alborán está influenciada significativamente por las corrientes atlánticas entrantes.

También señala lo difícil que resulta predecir cómo afectará el cambio climático a las pequeñas especies pelágicas debido a la falta de planes establecidos de monitoreo a largo plazo, a la escasez de datos y a los complejos cambios ambientales. El impacto del cambio ambiental en el funcionamiento de los ecosistemas en general, y en las pequeñas especies pelágicas en particular, requiere más estudios en el futuro.

La gestión y la conservación de las pequeñas especies pelágicas requieren una mejor comprensión de cómo el cambio climático y otros factores afectan a estas especies. Se necesitan investigaciones y modelos multidisciplinarios y de toda la cuenca, con enlaces a las bases de datos del norte y el sur, para mejorar nuestra comprensión de los impactos del cambio climático en estas especies y los ecosistemas que las sustentan.

En conclusión, las especies pelágicas pequeñas son componentes importantes de los ecosistemas marinos y fuentes importantes de alimento para los seres humanos y los grandes depredadores. Comprender y gestionar el impacto del cambio climático y otros impactos en estas especies es fundamental para garantizar su supervivencia a largo plazo y promover la gestión sostenible y los esfuerzos de conservación.. Al mismo tiempo, otros factores además de los cambios ambientales también pueden ser responsables de la disminución de los desembarques de esta especie.. Como esta especie es la especie pelágica pequeña más comercializada en el área de estudio, la sobrepesca de esta especie puede ser un posible factor que contribuya a la disminución a largo plazo de los desembarques.

(French)

Les débarquements à long terme des petits poissons pélagiques (sardines, anchois et maquereaux) entre 1983 et 2020 ont connu des changements majeurs dans le sud de la mer d'Alboran. Bien que l'impact de l'augmentation de la pression de pêche doive être pris en compte dans les travaux futurs, le manque actuel de données sur l'effort de pêche ne permet aucune analyse sur cette question.

Le modèle linéaire reflète les effets possibles du réchauffement de la mer d'Alboran (probablement lié au changement climatique) et de la réduction de l'énergie cinétique de l'AJ sur la tendance observée à la baisse des débarquements de sardines. Les impacts prévus du changement climatique incluent une stratification accrue de la colonne d'eau et une réduction du mélange hivernal, réduisant ainsi l'injection de nutriments dans la zone photique et diminuant l'intensité des efflorescences phytoplanctoniques hivernales et printanières. Jusqu'à présent, ces changements n'ont pas été observés dans la mer d'Alboran, et les séries chronologiques sur la chlorophylle montrent une tendance positive. Cela peut s'expliquer par le fait que l'effet du réchauffement de l'océan sur la stratification de la colonne d'eau méditerranéenne peut être compensé par un effet inverse associé à une augmentation de la salinité.. Une autre possibilité est que la mer d'Alboran soit influencée par des mécanismes de remontée d'eau spécifiques. Les concentrations de chlorophylle dans les eaux de surface semblent être un facteur important régulant la variabilité des débarquements annuels de sardines. Enfin, pour les variations à long terme et interannuelles, le modèle linéaire a pu expliquer environ 60 % de la variance à l'atterrissage.

D'autre part, lors de la modélisation des données de tendance temporelle, il a été constaté que les débarquements d'anchois variaient de manière significative. Le SST, le SSS et le vent en U sont les principaux facteurs environnementaux affectant l'abondance des anchois. Cependant, les facteurs environnementaux n'ont pas pu expliquer la variation des débarquements d'anchois après la suppression de la composante tendancielle.. Cela peut indiquer que les facteurs environnementaux, tout en ayant des effets à long terme, ont peu d'effet sur les échelles de temps interannuelles.

En ce qui concerne les effets possibles des changements environnementaux sur le maquereau de l'Atlantique. Les résultats suggèrent que cette espèce pourrait être plus sensible à la salinité, à la température, aux courants océaniques et à la configuration des vents, ainsi qu'à l'abondance d'anchois (proies), et que les modifications de ces variables peuvent affecter leur abondance et, en fin de compte, leur exploitation halieutique. Ces résultats démontrent la nécessité de prendre en compte l'impact des processus océanographiques lors de la gestion de ces ressources halieutiques et suggèrent que la dynamique de ces populations de poissons pélagiques dans la mer d'Alboran est influencée de manière significative par les courants atlantiques entrants.

Il note également à quel point il est difficile de prévoir l'impact du changement climatique sur les petites espèces pélagiques en raison de l'absence de plans de suivi à long terme établis, de la rareté des données et de la complexité des changements environnementaux. L'impact des changements environnementaux sur le fonctionnement des écosystèmes en général, et sur les petites espèces pélagiques en particulier, doit être étudié plus avant à l'avenir.

La gestion et la conservation des petites espèces pélagiques nécessitent une meilleure compréhension de la façon dont le changement climatique et d'autres facteurs affectent ces espèces. Des recherches et des modélisations multidisciplinaires à l'échelle du bassin, avec des liens vers des bases de données du nord et du sud, sont nécessaires pour améliorer notre compréhension des impacts du changement climatique sur ces espèces et les écosystèmes qui les soutiennent.

En conclusion, les petites espèces pélagiques sont des éléments importants des écosystèmes marins et d'importantes sources de nourriture pour les humains et les grands prédateurs. Il est essentiel de comprendre et de gérer l'impact du changement climatique et d'autres impacts sur ces espèces pour garantir leur survie à long terme et faire avancer les efforts de gestion et de conservation durables... Dans le même temps, des facteurs autres que les changements environnementaux peuvent également être responsables de la baisse des débarquements de cette espèce. Comme cette espèce est la petite espèce pélagique la plus commercialisée de la zone d'étude, la surpêche de cette espèce pourrait être un facteur susceptible de contribuer au déclin à long terme des débarquements.

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