

# Variability of oceanographic and meteorological conditions in the northern Alboran Sea at seasonal, inter-annual and long-term time scales and their influence on sardine (*Sardina pilchardus* Walbaum 1792) landings

Manuel Vargas-Yáñez  | Ana Giráldez | Pedro Torres  | María González  |  
María del Carmen García-Martínez  | Francina Moya 

Centro Oceanográfico de Málaga, Instituto Español de Oceanografía, Fuengirola, Spain

## Correspondence

Manuel Vargas-Yáñez, Centro Oceanográfico de Málaga, Instituto Español de Oceanografía, Fuengirola, Málaga, Spain.  
Email: manolo.vargas@ieo.es

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## Abstract

Time series of European sardine (*Sardina pilchardus*) landings from 1962 and environmental variables from 1978 in the northern Alboran Sea are analysed. European sardine spawns in the northern Alboran Sea from mid-autumn to late winter at a temperature range slightly higher than the one observed in the nearby Eastern North Atlantic and the North Western Mediterranean. Individuals hatched during autumn and winter are incorporated to the fishery during the following summer and autumn producing the maximum annual landings. These landings show both a decreasing long-term trend and a strong inter-annual variability. Although further research is needed, the warming trend of sea surface temperature and the decrease in upwelling intensity inferred from empirical orthogonal function (EOF) analyses could have some influence on the negative trends of sardine landings. The inter-annual variability of sardine abundance seems to be related to the wind intensity at a local scale, the second principal component of the chlorophyll concentration and the sardine abundance during the preceding year. If the inter-annual variability is considered, a linear model including these three variables with a one-year time lag allows to explain 79% of the sardine landings variance. If the negative linear trend is also considered, the model explains 86% of the variance. These results indicate that the body condition of spawners, linked to the food availability during the preceding year, is the main factor controlling the recruitment success. The possibility of predicting sardine landings 1 year in advance could have important implications for fishery management.

## KEYWORDS

Alboran Sea, European sardine, inter-annual variability, linear model, long-term changes, Mediterranean Sea, multi-model inference

## 1 | INTRODUCTION

Clupeoid fishes play a fundamental role in marine ecosystems as they connect primary and secondary producers with predatory fishes, marine mammals and seabirds. This intermediate position within

the food web allows small pelagic fishes to exert a wasp-waist control on both higher and lower trophic levels (Costalago, Palomera, & Tirelli, 2014; Garrido & Van der Lingen, 2014; Shannon, Field, & Moloney, 2004). For these reasons, fluctuations in the clupeoid populations could be of great importance for the ecosystems, affecting

the whole trophic web. Besides a strong inter-annual variability, these fluctuations exhibit large oscillations that can lead to regime shifts with changes in the dominance of different species such as sardines and anchovies (Lindegren, Checkley, Rouyer, MacCall, & Stenseth, 2013; Lluch-Cota, 2013; Shannon et al., 2004).

Because of the short life span, high fecundity and early maturation of most clupeoid species, inter-annual variability of these populations is highly dependent on the annual recruitment success (Ganias, Somarakis, & Nunes, 2014; Katara, 2014). This, in turn, is strongly conditioned by environmental factors (Brosset et al., 2015, 2017; Katara, 2014; Tugores et al., 2011). Understanding the variability of clupeoid populations and how it is affected by environmental variables is of paramount importance for the correct management of these resources (Cole, 1999; Cole & McGlade, 1998; Ganias et al., 2014). On the other hand, several works have already revealed that changes caused by climate change could alter the abundance and the distribution (both in latitude and in depth) of fish populations (Tzanatos, Raitsos, Triantafyllou, Somarakis, & Tsonis, 2014). A better understanding of the relations between small pelagic fishes and environmental factors could help to predict how climate change and other stressors will affect these fish populations in the near future.

The main factors that determine the recruitment success are the sea temperature, the food availability, the intensity of upwelling processes, the turbulent kinetic energy and the oceanographic structures that could produce the retention and advection of eggs and larvae to nursery grounds (Bakun, 1996). Sea temperature controls the maturation of adults (Ganias et al., 2014; Stratoudakis et al., 2007) and the growth rate during the embryonic and larval stages (Riveiro, Guisande, Maneiro, & Vergara, 2004) when mortality rates are maxima because of predation and starvation. Larvae of sardine and anchovy species have a particulate selective feeding on small zooplankton, while adults can alternate particulate selective and filter feeding, and prey on both zoo- and phytoplankton (Costalago & Palomera, 2014; Costalago et al., 2014; Van der Lingen et al., 2009). Fertilizing processes such as wind-induced upwelling or mesoscale structures can enhance primary and secondary production increasing food availability for both adults and larvae. In the case of adults, food availability improves body condition increasing the number and size of eggs (Brosset et al., 2017; Brosset, Lloret, et al., 2016). In the case of larvae, food availability is a determinant factor for the larval survival (Katara, 2014).

Changes in the wind intensity and the onset of the upwelling season can also be related to changes in the main atmospheric circulation patterns such as the North Atlantic Oscillation (NAO, Guisande, Vergara, Riveiro, & Cabanas, 2004) and the Pacific Decadal Oscillation (PDO, Lindegren et al., 2013). These complex interactions have been synthesized in comprehensive models: Bakun triad (Bakun, 1996), match/mismatch hypothesis (Cushing, 1990) or the optimal environmental window (Cury & Roy, 1989).

In the particular case of the Mediterranean Sea, European sardine (*Sardina pilchardus*) and European anchovy (*Engraulis encrasicolus*) represent 16% and 22% of total annual catches (FAO, 2018),

having a great importance both from an ecological and commercial point of view. Several works have evidenced the influence of the sea temperature on the onset and the duration of the breeding season (Sabatés, Olivar, Salat, Palomera, & Alemany, 2007). Lloret et al. (2015) have also evidenced that the warming of the Mediterranean Sea has shortened the spawning season and the reproduction area for cold-water species such as European sardine, while thermophilic species have widened northwards their distribution range (Sabatés, Salat, Raya, Emelianov, & Segura-Noguera, 2009). Besides the effects of sea temperature on the small pelagic distributions, changes in the water column stratification and their possible influence on the productivity of the sea and the composition of the zooplanktonic communities could have induced changes in the body condition and population structure of sardines and anchovies in the North Western Mediterranean (Brosset et al., 2017; Brosset, Le Bourg, et al., 2016).

Wind intensity is another mechanism capable of relaxing the oligotrophy of the Mediterranean Sea (Martín et al., 2008; Sabatés, Olivar, et al., 2007). Martín et al. (2008) have evidenced that higher catches and higher larval growth rates were found for areas with high chlorophyll concentrations. River discharges constitute another factor responsible for the injection of nutrients at the photic layer, enhancing primary and secondary production (Lloret, Palomera, Salat, & Solé, 2004). Sabatés, Salat, et al. (2007) have shown that the estuaries of the rivers Rhône and Ebro are the main spawning areas for anchovies in the North Western Mediterranean.

Besides the favourable conditions at the spawning grounds, the larval survival requires the existence of retention mechanisms which avoid the egg and larval dispersion and that guarantee their advection to nursery grounds. Anchovy and sardine eggs and larvae accumulate in the frontal system associated with the extension of the Northern Current in the Catalan Sea continental slope (Sabatés, Olivar, et al., 2007; Sabatés, Salat, et al., 2007). Eddies developed from this current could act as retention structures favouring larval survival. García-Lafuente et al. (2002) have shown that sardine larvae were transported at the frontal system associated with the Atlantic-Ionian Stream to the south of Sicily Island. These larvae were finally advected to a cyclonic eddy at the south-eastern extreme of Sicily that would act as a retention/nursery area.

In the particular case of the Alboran Sea, there are very few works trying to establish and quantify the relationships between the abundance, distribution and condition of European sardine and other small pelagic fishes with environmental factors. Some of these works are those by Jghab et al. (2019) and Abdellaoui et al. (2017), which have suggested the existence of some relations between the inter-annual variability of sardine catches in the Moroccan coast and the sea surface temperature and salinity (SST, SSS), chlorophyll concentration and the kinetic energy of the Atlantic Jet (AJ) flowing through the Strait of Gibraltar. Concerning the northern shore of the Alboran Sea, Ruiz et al. (2013) hypothesized that the kinetic energy of the AJ could be a negative factor for anchovy recruitment in the northern Alboran Sea, as it would increase egg and larval dispersion.

This work is aimed at the analysis of the seasonal, inter-annual and long-term variability of sardine catches in the northern coast of the Alboran Sea and the description of the atmospheric and oceanographic conditions that could affect such variability. It is a first attempt to model the influence of environmental factors on the inter-annual variability of sardine abundance.

## 2 | DATA

### 2.1 | Sardine landings and biological data

Sardine landings data were obtained at the following ports from the northern Alboran coast: La Atunara, Estepona, Marbella, Fuengirola, Málaga, Vélez, Motril, Adra, Roquetas and Almería (Figure 1). Annual landings data were expressed in metric tons (t), and they were available from 1962 to 2017. Annual fishing effort data (effective fishing nights) were obtained from 1990 to 2017. Finally, landings and fishing effort data disaggregated by months were available from 2003 to 2017. Both annual and monthly data were added for the ten ports cited above, and a single value for the northern Alboran Sea was obtained for each of the following variables: annual landings, monthly landings, fishing effort and landings per unit effort (LPUE). Lloret et al. (2004) showed that landings could be representative of LPUE for periods when the fishing effort had remained stable. Froese, Zeller, Kleisner, and Pauly (2012), Jghab et al. (2019), Tzanatos et al. (2014), have also shown that captures could be representative of the fluctuations in sardine biomass. Annual time series of LPUE in the northern Alboran Sea span from 1990 to 2017, whereas annual landings extend from 1962 to 2017. Therefore, annual landings time series were used for the analysis of inter-annual and long-term variability after checking the correlation with LPUE.

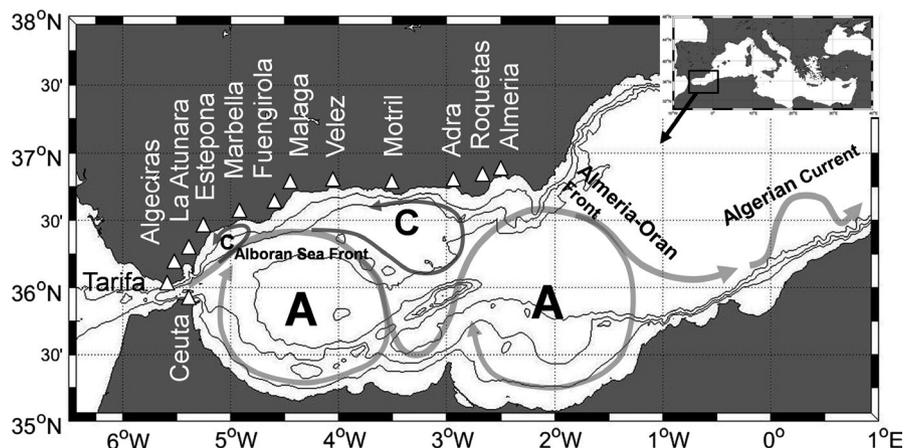
From 1989 to 1996 and from 2003 to 2017, a biological sampling was carried out from commercial landings. Total size (to the

nearest millimetre), total weight and gonad weight (to the nearest 0.1 g) were sampled. A gonadosomatic index was calculated as the ratio between the gonad and the total weight.

### 2.2 | Surface chlorophyll and sea surface temperature (SST)

Monthly surface chlorophyll (*Chl*) concentration data were obtained from NASA Ocean Biology Processing Group (OBPG, <https://ocean.color.gsfc.nasa.gov/>). Data from the coastal zone color scanner (CZCS) were available from November 1978 to June 1986. Data from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) were obtained from September 1997 to December 2010, and data from the Moderate-Resolution Imaging Spectroradiometer (MODIS) Aqua, from January 2011 to December 2017. Monthly sea surface temperature (SST) data from November 1981 to December 2017 were obtained from the NOAA/OAR/ESRL PSD, Boulder, Colorado (<https://www.esrl.noaa.gov/psd/>, Reynolds, Rayner, Smith, Stokes, & Wang, 2002).

For each month, *Chl* and SST values were calculated in two different ways. The first one was the average value for the northern sector between 5.5°W and 2°W and between 36°N and the northern coast of the Alboran Sea. The time series obtained in this way were considered as representative of the general conditions in the area of study. Nevertheless, several works have evidenced that sardine spawns over the continental shelf both in the North Western Mediterranean and in the Alboran Sea (Morote, Olivar, Villate, & Uriarte, 2010; Olivar, Salat, & Palomera, 2001; Sabatés, Olivar, et al., 2007). On the other hand, Cole and McGlade (1998) suggested that local environmental variables were more appropriate to predict the recruitment success than those variables averaged over larger geographical regions. For these reasons, *Chl* and SST monthly values were also averaged for a strip extending 14 km southwards from the coast for the case of the chlorophyll concentration and 28 km for the case of SST.



**FIGURE 1** Location of the Alboran Sea position of the ports in its northern coast where sardine landings data were collected. Mean sea level data were obtained from the IEO tide gauges at Algeciras, Ceuta and Tarifa, also included in this figure. A scheme of the most frequent circulation patterns within the Alboran Sea has been included. Anticyclonic circulation areas are marked as A and cyclonic circulation ones as C. The Alboran Sea frontal system, the Almería-Orán front and the Algerian Current are also indicated

## 2.3 | Meteorological data

Reanalysis Derived data were obtained from NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website at <https://www.esrl.noaa.gov/psd/> (Kalnay et al., 1996). These data have a low spatial resolution and were considered in the present work as representative of general conditions in the whole Alboran Sea. The variables considered were as follows: air temperature, the west–east and south–north components of the wind, the atmospheric pressure and the precipitation. In order to get information about the meteorological conditions on a local scale, air temperature, wind intensity (velocity magnitude), atmospheric pressure and precipitation data were collected from the Málaga and Almería meteorological stations (Figure 1). These data were provided by the Spanish Meteorological Agency (AEMET, <https://datosclima.es>). Coarse-resolution meteorological data (NCEP) were monthly and were collected from 1981 to 2017. Local meteorological data (AEMET) were daily and were obtained from 1978 to 2017. Monthly values were obtained from the daily time series.

## 2.4 | Sea level data

Monthly sea level data at Ceuta, Algeciras and Tarifa (Figure 1) from 1962 were obtained from the tide gauge network operated by the Instituto Español de Oceanografía (IEO, Spanish Institute for Oceanography). Ceuta time series extends to 2017, whereas Algeciras sea level data stop in 2002. The gap in Algeciras data (from 2002 to 2017) was filled using a linear regression between Ceuta and Tarifa sea level time series. Finally, a time series of cross-strait sea level differences between Ceuta and Algeciras was obtained from 1962 to 2017. This variable can be considered as proportional to the velocity of the Atlantic Current flowing through the Strait of Gibraltar (Jhab et al., 2019).

## 2.5 | Atmospheric circulation indexes

Following Brosset et al. (2017), Guisande et al. (2004), Thiaw et al. (2017), indexes for main atmospheric circulation patterns were considered. Annual and winter North Atlantic Oscillation (NAO) values were collected from Hurrell, James & National Center for Atmospheric Research Staff (Eds), last modified 04 August 2018: “The Climate Data Guide: Hurrell North Atlantic Oscillation (NAO) Index (station-based)” retrieved from <https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based>. Winter NAO index (NAO\_DJFM) was calculated for each year as the mean value of the December value corresponding to the previous year and the January, February and March values for the current one.

Monthly data for the Mediterranean Oscillation Index (MOI) and the Western Mediterranean Oscillation index (WeMOI) were

obtained from the Climatic Research Unit, University of East Anglia (<https://crudata.uea.ac.uk/cru/data/moi/>), and the Climatology Group from Barcelona University ([www.ub.edu/gc/es](http://www.ub.edu/gc/es)), respectively. MOI was calculated as the difference in normalized sea level pressure between Gibraltar and Israel, whereas WeMOI was defined as the difference in normalized sea level pressure between Padua (Italy) and San Fernando (Spain). In both cases, annual and winter (MOI\_DJFM, WeMOI\_DJFM) values were calculated from the monthly time series. The final time series extend from 1962 to 2017. Table S1 in Appendix S1 summarizes the time series used in the present work and their length.

## 3 | DATA PROCESSING

### 3.1 | Seasonal cycles and linear trends

The homogeneity of all time series was checked using homogeneity tests (see Alexandersson, 1986 and Appendix S1 for mathematical details). Then, monthly sardine landings (from 1990 to 2017) and environmental variables were grouped by month of the year. The normality of the data was checked by means of Shapiro–Wilk tests. For each month, a mean value, a standard deviation and a 95% confidence interval (using a *t*-Student distribution) were estimated. The set of twelve monthly mean values define the climatological or average seasonal cycle. A non-parametric Kruskal–Wallis test was performed to detect differences between the twelve monthly mean values. A Tukey honestly significant difference test was also applied to detect the months with a different behaviour. In order to smooth the seasonal cycle of the sardine landings, one harmonic with annual (12 months) periodicity was fitted.

Once the seasonal cycles were obtained, monthly time series were annually averaged to obtain annual time series for all the variables described above. Linear trends representing long-term changes were estimated fitting a straight line by means of least squares. Confidence intervals for the slope of the linear fit were calculated considering a *t*-Student distribution and taking into account the effective degrees of freedom (see Emery & Thomson, 1998 and Appendix S1).

### 3.2 | Empirical Orthogonal Functions

Cole (1999) has shown that principal component (PC) analysis could be an efficient method to characterize oceanographic structures that could act as retention mechanisms. Jhab et al. (2019) also found that empirical orthogonal function (EOF, similar to principal component analysis) could be used in the prediction of sardine landings in the southern Alboran Sea. For these reasons, oceanographic structures were identified by means of EOF analysis (see Preisendorfer, 1988 and Appendix S1 for the mathematical details).

### 3.3 | Inter-annual variability: Exploratory analyses

Once the time series had been annually averaged and linear trends had been subtracted, the remaining time variability of sardine landings and environmental variables was mainly inter-annual. One of the goals of the present work was to find the best approximating linear model to explain such time variability. The response variable was the sardine landings, but many environmental variables could be considered as potential predictors. These variables were as follows: *Chl* and *SST*, the amplitude time series (principal components) associated with *Chl* and *SST* EOFs, east–west and north–south components and intensity of the wind, air temperature, atmospheric pressure and precipitation time series, and annual and winter NAO, MOI and WeMOI time series. 30 environmental time series were considered as potential predictors. This number increased if time series with a one-year time lag were also taken into account. This is an excessive number of potential predictors. For this reason, an exploratory analysis was carried out. Each potential predictor was plotted against sardine landings, and the correlation between both variables was calculated. Only those variables significantly correlated at the 0.1 significance level were retained as potential predictors.

The number of potential predictors after this exploratory analysis was reduced to eight (see results section). Any combination of these eight predictors could be considered as a candidate model. If all the possible combinations were considered, the number of candidate models would be 255. This number is excessive. Therefore, the following procedure was used for selecting a reduced set of candidate models (Jghab et al., 2019). Considering the different length of the available time series, the complete data set was made of time series extending from 1981 to 2017. Then, the first year (1981) was suppressed and the response variable was linearly regressed on the eight potential predictors using a forward stepwise method. The linear regression selected a model with only a certain number of predictors. Then, the second year of the time series was suppressed and the stepwise linear regression was applied to select a new model. This procedure was repeated 37 times, leaving out a different year for each time. Only those models (combinations of predictors) that were selected at any of the 37 trials were finally considered as candidate ones.

### 3.4 | Model selection and multi-model inference

For each candidate linear model, the Akaike information criterion, corrected for small samples, was calculated. Models were ordered from the lowest to the highest value of *AICc*. Then, the relative likelihood and the probability of each model were calculated (Burnham & Anderson, 2004; Burnham, Anderson, & Huyvaert, 2011, see also Appendix S1 for mathematical details).

Once the best approximating model was selected according to the minimum *AICc* criterion, the coefficients of the linear model were estimated using a linear combination of the coefficients obtained for each candidate model. The weights in this linear combination were

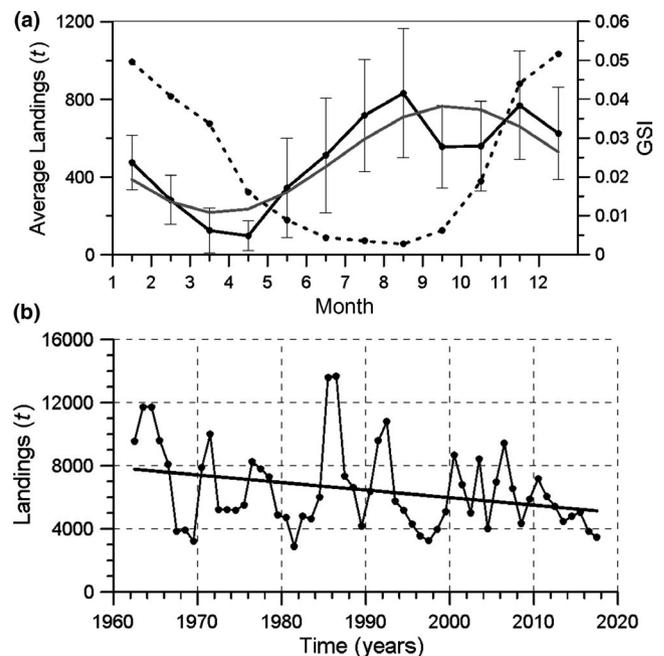
the probabilities associated with each candidate model. Finally, the variance for each coefficient considered the uncertainty of the parameter estimation for each model and the uncertainty associated with the model selection (Burnham & Anderson, 2004; Burnham et al., 2011; and Appendix S1).

Finally, using the best approximating model and the coefficients inferred from the multi-model approach, the sardine landings time series was reconstructed, and the explained variance was analysed. In this way, it was checked the suitability of the selected model for explaining the observed variance and predicting sardine landings.

## 4 | RESULTS

### 4.1 | Sardine landings: seasonal cycle and linear trends

Average sardine landings are minimum at late winter or early spring (98 tons per month) and increase during spring and summer, reaching maximum values that range between 832 and 769 tons per month, from August to November (Figure 2a). Both ANOVA (considering normality) and Kruskal–Wallis (non-parametric) tests confirmed the existence of differences between the mean values corresponding



**FIGURE 2** (a) Black line shows the average seasonal cycle for sardine landings at the northern coast of the Alboran Sea. Error bars are the standard deviation for each month of the year. To construct this seasonal cycle, all the values from the complete time series (1962–2017) corresponding to each month of the year were averaged. For instance, the 56 January values were averaged to obtain the mean January value. The grey line is a sinusoidal (one harmonic) seasonal cycle fitted by least squares. The dashed line is the seasonal cycle for the gonadosomatic index. (b) shows the annual landings time series. A straight line representing the linear trend is included

to each month of the year. A Tukey honestly significant difference test revealed that average landings for March and April (minimum values) were significantly different from those values corresponding to August and November (maximum mean values), but no significant differences were observed from July to November. Therefore, the slight decrease in average landings during September and October was not statistically significant. Grey line in Figure 2 shows a smoothed seasonal cycle estimated as an annual mean value and one harmonic with a twelve-month period.

The homogeneity test revealed some non-homogeneities from 1964 to 1966 (see Figure S2a in Appendix S1). Both annual and monthly landings were significantly correlated with LPUE, explaining 70% of the LPUE variability (Figure S2b,c). This result and the longer length of landings time series justify its use instead of LPUE.

Adding the average landings for the 12 months of the year, the annual average landings were 5,896 t. Landings showed a continuous decrease from the beginning of the time series in 1962 with a negative trend of  $-48 \pm 42$  t/year (Figure 2b, see Table S2 in Appendix S1 for a summary of the trends estimated for the sardine landings and the environmental variables analysed).

The gonadosomatic index (dashed line in Figure 2a) is maximum during December and January and remains high during November, February and March. Then, it drops to low values from April to October.

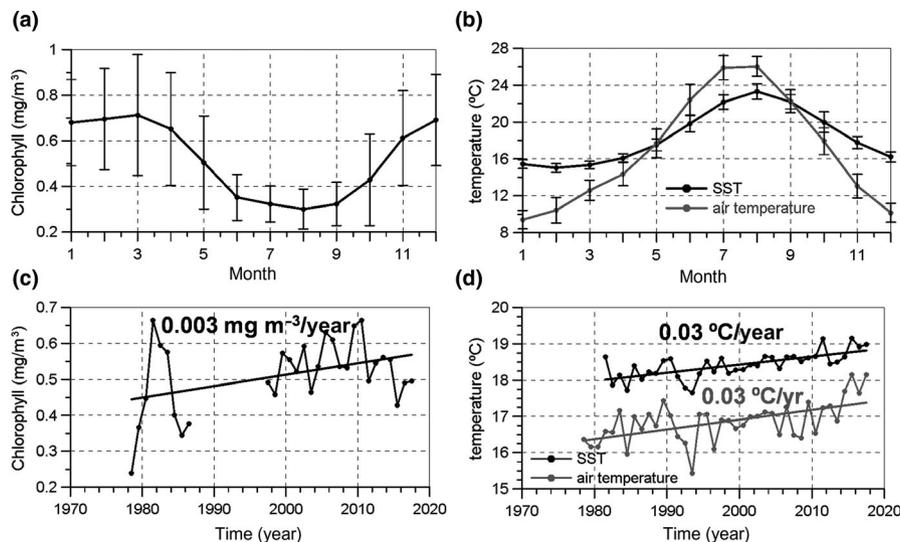
## 4.2 | Surface chlorophyll concentration and SST: seasonal cycle and trends

Chlorophyll concentrations reached maximum values ( $\sim 0.7$  mg/m<sup>3</sup>) at late winter or early spring and then decreased to minimum values from July to September ( $\sim 0.3$  mg/m<sup>3</sup>). On the contrary, SST reached minimum values in winter, with a value around 15.0°C

during January/February, and reached a maximum value in August (23.3°C, Figure 3a,c). The only non-homogeneities were detected in the chlorophyll time series during 1979 and 1980 (Figure S3a,b). Chlorophyll concentrations experienced a significant trend but its value was very low with an increasing rate of  $0.003$  mg m<sup>-3</sup> year<sup>-1</sup>. On the contrary, SST showed a significant and strong positive trend of  $0.03 \pm 0.01$ °C/year (Figure 3b,d) representing 63% of the SST variance (Table S2).

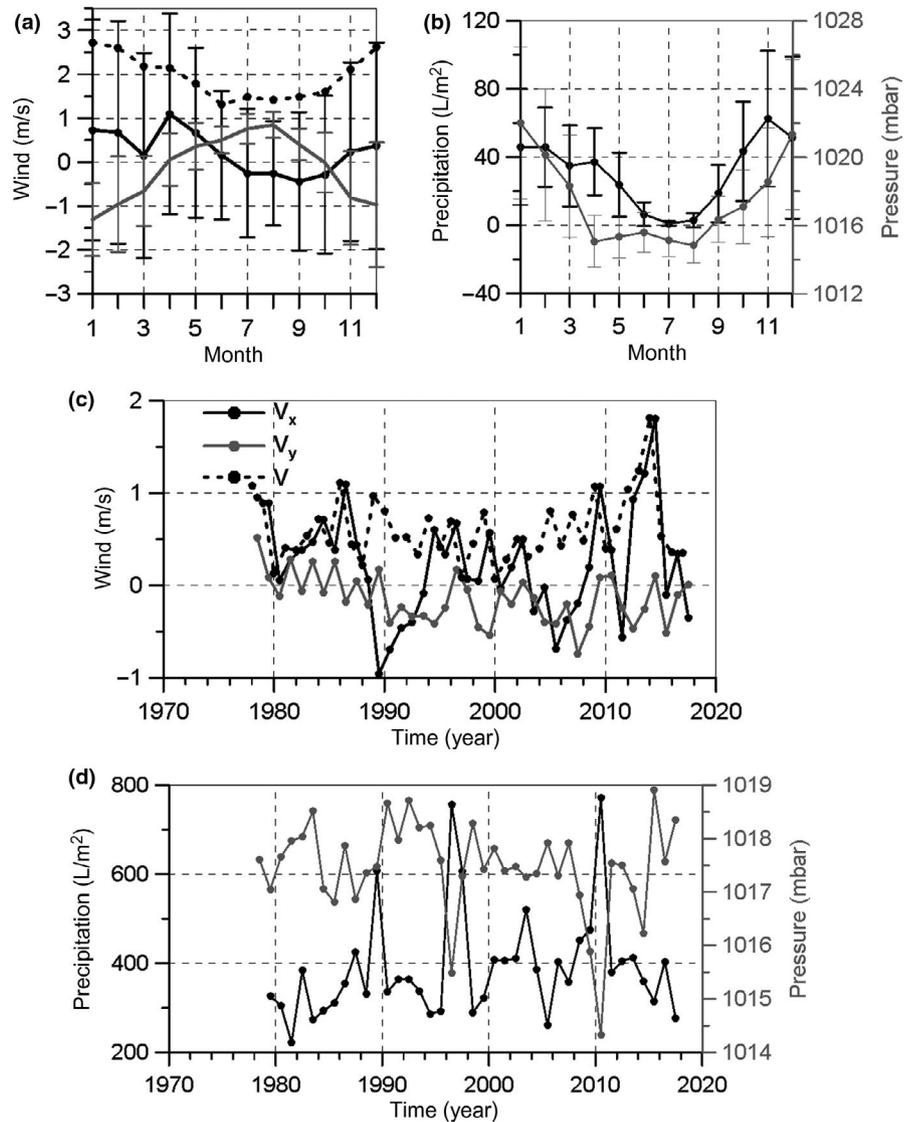
## 4.3 | Wind, atmospheric pressure and precipitation data: seasonal cycles and trends

Figure 4a shows the average seasonal cycle for the west-east ( $V_x$ ) component of the wind (black line), the south-north ( $V_y$ ) component (grey line) and wind intensity (black dashed line), using NCEP Reanalysis data for the northern half of the Alboran Sea. Notice that both  $V_x$  and  $V_y$  are considered as positive when the wind is directed to the east and to the north. According to Figure 4a, the average wind vector flows from the north-west (towards the south-east) during winter and spring. The prevailing winds are from the south-east (towards the north-west) during summer, and then, wind returns to blow from the north-west from November. The wind intensity (magnitude) follows a seasonal cycle similar to that of  $V_x$ . Higher intensities are coincident with westerly winds ( $V_x > 0$ ), whereas lower intensities are observed during summer coinciding with the prevalence of easterly winds ( $V_x < 0$ ). The estimated average seasonal cycles for precipitation and atmospheric pressure were similar, with minimum values in summer (0 mm/month for precipitations and 1,015 mbar for atmospheric pressure) and maximum values in autumn and winter (40–60 mm/month and 1,022 mbar, respectively, Figure 4b).



**FIGURE 3** (a) Average seasonal cycle for the surface chlorophyll concentration at the northern Alboran Sea. Error bars are the standard deviations for each month of the year. (b) Annual time series of chlorophyll concentration in the northern Alboran Sea. The value of the significant linear trend has been included. (c) The black line is the average seasonal cycle for SST, and the grey line is the seasonal cycle for the air temperature, both at the northern Alboran Sea. Error bars are standard deviations. (d) Annual time series of SST (black line) and air temperature (grey line) in the northern Alboran Sea. The values of the significant linear trends have been included

**FIGURE 4** (a) Average seasonal cycles for the west–east component ( $V_x$ ) of the wind (black line, positive when directed towards the east), south–north component ( $V_y$ ) of the wind (grey line, positive when directed towards the north) and wind intensity ( $V$ , dashed black line). (b) Average seasonal cycle for the precipitation (black line) and atmospheric pressure (grey line) in the northern Alboran Sea. Error bars for figures (a) and (b) are the standard deviations. (c) Annual time series of  $V_x$  (black line),  $V_y$  (grey line) and  $V$  (black dashed line). (d) Annual time series for precipitation (black line) and atmospheric pressure (grey line)



Meteorological time series did not show any non-homogeneity. The two Cartesian components of the wind and the wind intensity showed no significant trends (Figure 4c). No trends for the precipitation and atmospheric pressure were observed (Figure 4d). In the case of meteorological data from local weather stations (Málaga and Almería, Figure 1), the results obtained were similar to those described for the Reanalysis data, with maximum wind intensities, atmospheric pressure and precipitation during autumn and winter, and minimum values during summer. The only difference was a significant positive trend for the wind intensity at Almería (Table S2). These time series are not shown for the sake of brevity.

#### 4.4 | Sea level and atmospheric circulation indexes

Both the monthly sea level time series at Algeciras and Ceuta showed clear seasonal cycles with minimum values in February and maximum ones in October. A Kruskal–Wallis test also revealed the existence of significant differences for the cross-strait sea

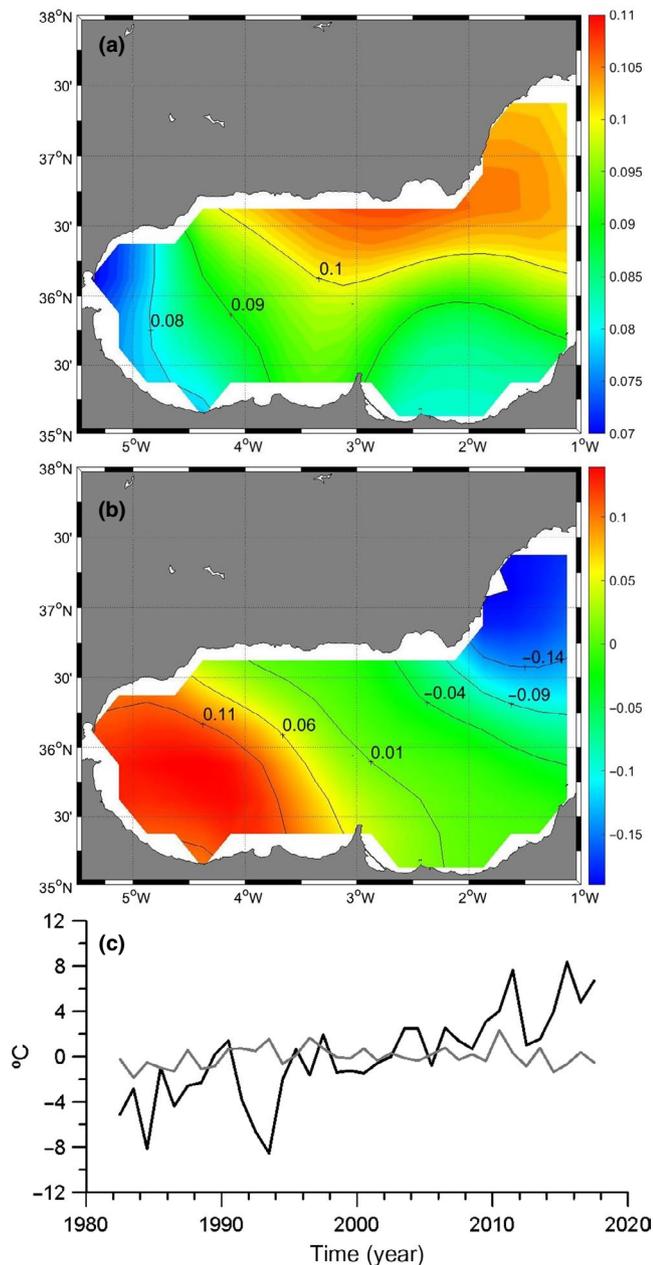
level difference ( $p = .02$ ). A Tukey honestly significant difference test showed that minimum values in October/November were significantly different from maximum ones from April to June at the 0.1 significance level. Although the annual mean sea level rose at Algeciras and Ceuta at rates of  $0.9 \pm 0.3$  mm/year and  $0.7 \pm 0.3$ , respectively, the cross-strait sea level difference did not experience any significant long-term change and only inter-annual variability was observed.

In the case of NAO, MOI and WeMOI, only annual or winter time series were analysed, and therefore, no seasonal cycles were estimated. No significant trends were observed for any of these indexes.

## 5 | EMPIRICAL ORTHOGONAL FUNCTIONS

The first EOF for both SST (Figure 5a) and surface chlorophyll concentration (Figure 6a) shows no sign changes for the whole Alboran Sea and represents in-phase oscillations of the temperature and chlorophyll for the whole Alboran Sea. Black line in Figure 5c is the

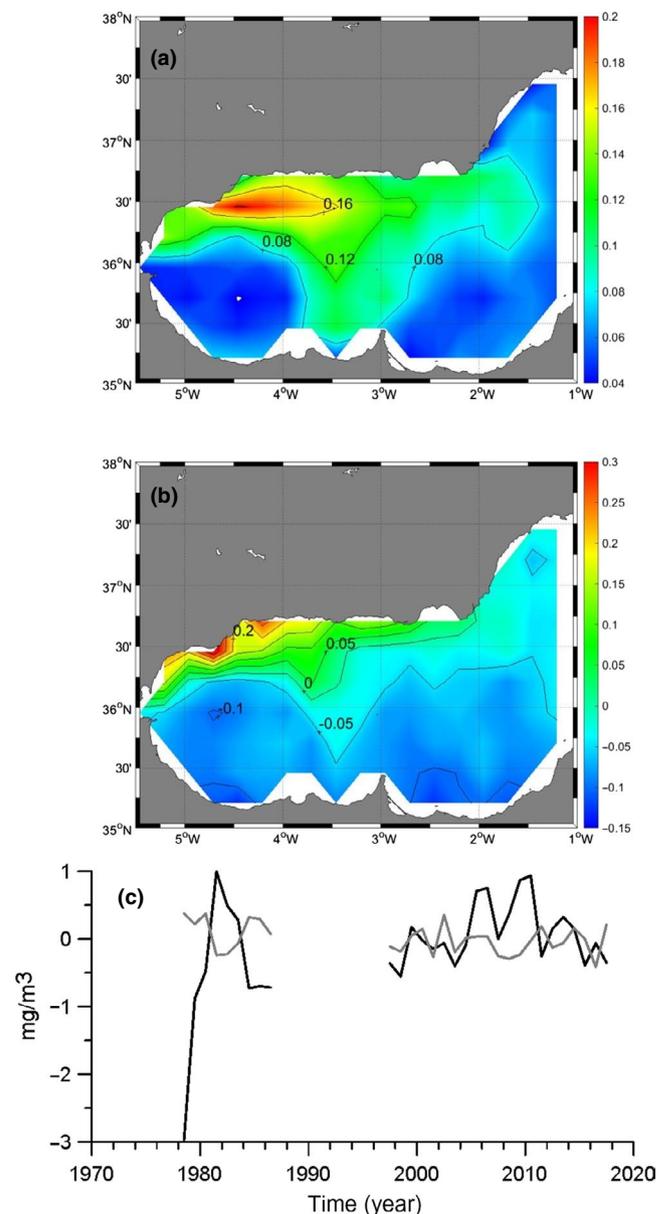
amplitude (PC) associated with the first SST EOF. It is characterized by a strong positive trend. According to the spatial distribution of this first EOF (see Figure 5a), the warming of the Alboran Sea would be more intense at its north-eastern sector and less intense in the area close to the Strait of Gibraltar. The amplitude of this first mode accounts for more than 80% of the SST variance (Figure S5a in Appendix S1). This behaviour is similar to the one observed for the SST averaged for the northern Alboran Sea, as the linear trend for that time series accounted for 63% of the variance (Table S2). The second EOF for SST shows oscillations of different sign for the south-western sector of the Alboran Sea (positive weights in Figure 5b) and for the north-eastern area (negative weights, Figure 5b). The



**FIGURE 5** (a) First EOF for SST. Colours and contour lines indicate the spatial weights at each location. (b) Second EOF for the SST. (c) Amplitudes (principal components, PC) for the first (black line) and second (grey line) modes of SST

amplitude associated with this EOF (grey line in Figure 5c) only exhibits inter-annual variability. Positive values of the amplitude correspond to positive SST anomalies in the south-western part of the Alboran Sea (deviations from the average seasonal cycle) and negative SST anomalies in the north-eastern sector.

The first EOF for the surface chlorophyll concentration (Figure 6a) also reflects coherent oscillations for the whole Alboran Sea (positive weights for all the area), being the amplitude of such oscillations (black line in Figure 6c) more intense to the north of the most frequent position of the Atlantic Current and less intense in the inner parts of the anticyclonic gyres (see Figure 1 for a schematic of the Alboran Sea circulation). The amplitude



**FIGURE 6** (a) First EOF for surface chlorophyll concentration. Colours and contour lines indicate the spatial weights at each location. (b) Second EOF for surface chlorophyll concentration. (c) Amplitudes (principal components, PC) for the first (black line) and second (grey line) modes of chlorophyll concentration

associated with this EOF represents 30% of the variance (Figure S5b in Appendix S1) and is quite similar to the time evolution of the chlorophyll concentration at the northern Alboran Sea. The second EOF (Figure 6b) and its amplitude (Figure 6c) show oscillations of opposite sign to the north of the Atlantic Current and to the south, within the anticyclonic gyres.

## 6 | MODEL SELECTION AND MULTI-MODEL INFERENCE

An exploratory analysis revealed that the only variables, without time lag, that were significantly correlated with the annual sardine landings at the 0.1 significance level were the chlorophyll concentration averaged for the northern Alboran Sea, the wind intensity at Almería weather station for the northern continental shelf and the amplitude of the second EOF for the chlorophyll concentration. These time series will be named hereafter as  $Chl(t)$ ,  $Chl\_shelf(t)$ ,  $Va(t)$  and  $Chl\_A2(t)$ . Using time series with a one-year lag, the variables that were significantly correlated with sardine landings were the wind intensity at Málaga weather station, the amplitude of the second EOF for chlorophyll concentration and the sardine landings with a one-year time lag. These variables will be named hereafter as  $V_m(t-1)$ ,  $Chl\_A2(t-1)$  and  $S(t-1)$ .

The chlorophyll concentration averaged for the northern Alboran Sea and for the continental shelf was highly correlated ( $r = .94$ ); therefore, only the chlorophyll concentration averaged for the northern Alboran Sea was finally considered as a potential predictor. As wind intensity at Almería weather station was correlated with sardine landings when data from the same year were considered, and wind intensity at Málaga was correlated with sardine landings when a one-year lag was considered, both wind intensities at Almería and Málaga, with and without time lag, were considered as potential predictors. Finally, the set of potential predictors was made of eight variables:  $Chl(t)$ ,  $V_a(t)$ ,  $V_m(t)$ ,  $Chl\_A2(t)$ ,  $Va(t-1)$ ,  $V_m(t-1)$ ,  $Chl\_A2(t-1)$  and  $S(t-1)$ .

As  $Chl$  and  $SST$  data started in 1978 and 1981, respectively, and considering the non-homogeneities detected in the chlorophyll time series, the final data set extended from 1981 to 2017. A stepwise linear regression was repeated 37 times, leaving out a different year for each repetition. Five different models were selected (see the second column in Table 1), and these five models were considered as candidate ones. Using the complete time series, the  $AICc$  was calculated for each candidate model. The difference between the  $AICc$  value and the minimum value, and the probability for each model were calculated (fourth and fifth columns in Table 1. See data processing section and Appendix S1).

The first and second candidate models in Table 1 had similar support. Nevertheless, the second model, although has a slightly larger  $AICc$  value, seems to be a more reasonable one from a biological point of view, as it considers the influence of food availability, which is very likely to influence the larvae survival and the condition of spawners. Finally, the best approximating model for the inter-annual variability of sardine landings was as follows:

$$S(t) = \beta_0 + \beta_1 S(t-1) + \beta_2 V_m(t-1) + \beta_3 Chl\_A2(t-1) \quad (1)$$

The coefficients in this linear model were estimated using multi-model inference from the complete set of candidate models and the variance for each estimated coefficient considered both the uncertainty for each model and the uncertainty in the model selection (Table 2).

The model in expression (1) with the coefficients in Table 2 was used to reconstruct the sardine landings time series. Black line in Figure 7a is the time series of detrended sardine landings or anomalies. As chlorophyll time series starts in 1978 and has a gap from 1987 to 1996, red line in Figure 7a only shows the reconstruction for those years when chlorophyll data were available. Comparing the original time series of detrended landings and the estimation using the best approximating model, the variance explained is 79%. Blue line in Figure 7a is the reconstruction of the complete time series of detrended sardine landings, from 1962 to 2017, including the period 1987–1996. In this case, the sardine landings corresponding to those years when no chlorophyll data were available were estimated using the other two predictors. In this case, the explained variance was 63%.

To reconstruct the observed sardine landings (instead of the detrended ones), the existence of a linear trend must be taken into account. Annual sardine landings could be modelled as the sum of the linear trend (see Table S2) and the linear model for the inter-annual fluctuations:

$$S(t) = a + bt + \beta_0 + \beta_1 S(t-1) + \beta_2 V_m(t-1) + \beta_3 Chl\_A2(t-1) \quad (2)$$

Using expression (2) with the linear trend estimated in Table S2 the coefficients estimated from the multi-model inference (Table 2), the sardine annual landings were estimated for those years when the three predictors were available (red line in Figure 7b) and for the complete time series, using only the available predictors for each

**TABLE 1** Column 2 shows the variables included in the candidate model

Model	Variables	$AICc$	$\Delta_i$	$w_i$
1	$S(t-1) V_m(t-1)$	423.63	0	0.53
2	$S(t-1) V_m(t-1)$ $Chl\_A2(t-1)$	424.02	0.39	0.44
3	$V_m(t-1) V_a(t)$	430.43	6.8	0.02
4	$V_m(t-1) V_m(t)$ $V_a(t)$	431.23	7.6	0.01
5	$S(t-1)$	437.98	14.35	0.00

Note: Column 3 is the Akaike information criterion corrected for small samples ( $AICc$ ) calculated for each candidate model. Values within this column are ordered from the lowest to the highest value. Column 4 is the difference between the  $AICc$  values and the minimum value for each model, and column 5 shows the probabilities supporting each model as the best one (see Model selection and multi-model inference section and Appendix S1).

**TABLE 2** First column is the coefficient used in expressions (5) and (6), and second column shows the variables selected in the best approximating model

Coefficient	Predictor	$\hat{\beta}$	$\text{Var}(\hat{\beta})$	$S_{\hat{\beta}}$
$\beta_0$	Intercept	-235.1	117,750	343.2
$\beta_1$	$S(t-1)$	0.51	0.023	0.152
$\beta_2$	$V_m(t-1)$	4,022.3	794,530	891.4
$\beta_3$	$\text{Chl\_A2}(t-1)$	2,477.7	$2.63 \times 10^6$	1622.2

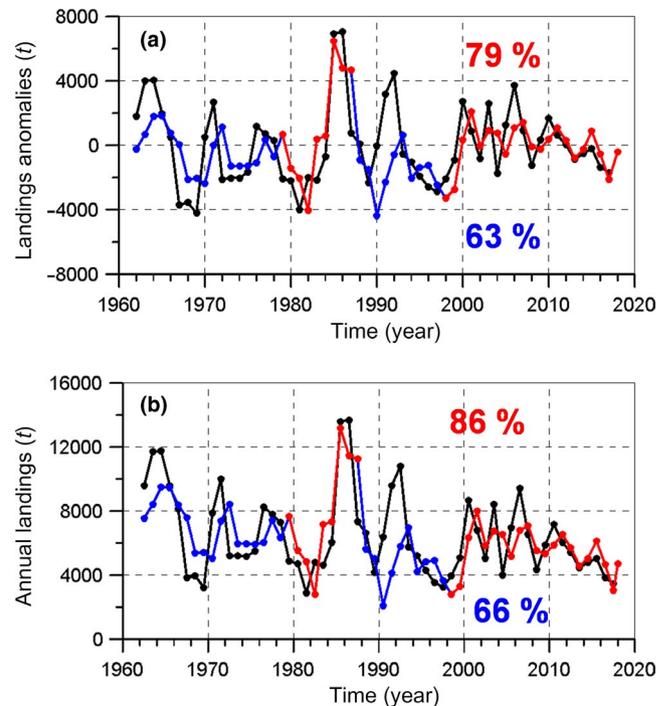
Note: The third column is the numerical value obtained for each coefficient using multi-model inference. The fourth and fifth columns are the variance and standard deviations for each coefficient (see Model selection and multi-model inference section and Appendix S1).

year (blue line in Figure 7b). The variance explained in both cases was 86% and 66%, respectively.

## 7 | DISCUSSION

The seasonal evolution of the gonadosomatic index (dashed line in Figure 2a) suggests that the spawning season for the sardines in the northern Alboran Sea would be from mid-autumn to the end of winter (November–March). This result had already been observed in other areas of the Eastern North Atlantic and the Mediterranean Sea (Abad & Giráldez, 1993; Domenella, Donato, & La Mesa, 2016; Sabatés, Olivar, et al., 2007; Silva et al., 2006; Somarakis et al., 2006). According to Stratoudakis et al. (2007), European sardine would spawn at waters between 14° and 15° C. Bernal et al. (2007) and Riveiro et al. (2004) provided similar temperature ranges for the sardine spawning season (13°–15° C). Palomera et al. (2007) reported a slightly lower temperature range (12°–14° C), but pointed out that spawning could also occur under temperatures as high as 19°C. According to SST data (Figure 3c), the temperature range for the sardine spawning season in the northern Alboran Sea would be 15.7°–18.2°C, warmer than the values previously reported. This difference must be caused by the dependence of the spawning temperature on latitude. Notice that Coombs et al. (2006) reported a temperature range of 14.6°–16.4°C for the Portuguese waters and 16°–18°C for the NW African waters.

The November–March period is also coincident with the highest values of chlorophyll concentration (> 0.6 mg/m<sup>3</sup>, Figure 3a). The chlorophyll cycle seems to be driven by the wind. The west-east component of the wind (Figure 4a, black line) shows the prevalence of westerly winds, which would favour upwelling processes from November to May. The period of westerly winds is also coincident with the highest intensity values (dashed line in Figure 4a). According to these results, it seems that the sardine spawning season in the northern Alboran Sea is coincident with the most productive period of the year. This productivity would be enhanced by Ekman transport upwelling (westerly winds) and the mixing of continental shelf waters (wind intensity).



**FIGURE 7** (a) Black dot line shows the anomalies or detrended time series of sardine landings for the northern coast of the Alboran Sea. The red line represents the anomalies reconstructed using the best approximating model and multi-model inference for the estimation of the model coefficients. The predictors in the best approximating model are  $S(t-1)$ ,  $V_m(t-1)$  and  $\text{Chl\_A2}(t-1)$ . Only those years when information from the three predictors is available are reconstructed (red line). The blue line is the reconstruction of the complete time series. For those years when chlorophyll data were not available, only two predictors were used: sardine landings and wind intensity at Málaga with a one-year lag. (b) shows the observed sardine landings (without detrending) and the reconstruction using the estimated linear trend plus the inter-annual variability predicted by the best approximating model. Once again, the red line corresponds to those years when chlorophyll data were available and the blue line corresponds to the complete time series

Besides upwelling and wind mixing, areas of cyclonic circulation would enhance primary production throughout the whole year (areas labelled as "C" in Figure 1; García-Martínez et al., 2019; Vargas-Yáñez et al., 2019). We speculate that, in addition to the fertilizing effect of the cyclonic gyres, they could also act as retention zones preventing larval dispersion. These structures would also provide shelter to sardine larvae and would protect them from the fast Atlantic Current. This would explain the lack of correlation between the sardine inter-annual variability and the cross-strait sea level difference, which is a proxy for the kinetic energy of the Atlantic jet.

The highest sardine landings are observed from July to December (black line in Figure 2a). Such high values would correspond to the incorporation of 0- or 1-year class recruits to the fishery. There is a slight decrease in catches during September and October. Nevertheless, a Tukey honestly significant difference test revealed that the average landings from July to December were not

statistically different. Taking into account this statistical result and the lack of any support for a decrease in the recruitment during September and October, a smooth seasonal cycle was fitted (grey line in Figure 2a). This cycle shows the minimum landings at the end of winter and beginning of spring, and the maximum landings at the end of summer and beginning of autumn.

Landings time series showed a decreasing trend of  $-48$  t/year from 1962 to 2017, whereas SST and air temperature increased at a rate of  $0.03^{\circ}\text{C}/\text{year}$  (Table S2) reflecting the current global warming. Several works have shown the potential impact of global warming on marine ecosystems. Burrows et al. (2011) showed that the displacement to the poles of isotherms and the changes in the onset and duration of seasons could alter the distribution ranges of marine organisms. Although these authors found that the changes in the Mediterranean Sea were less pronounced than in other regions of the world ocean, they pointed out that the movements of marine species in the Mediterranean Sea were constrained by land boundaries. Lloret et al. (2015) also reported a positive relationship between sea temperature and catches of warm-water fishes in the northern Catalan Sea. On the contrary, the warming of the water column produced the reduction in the abundances and distribution ranges of cold-water species. Brosset, Le Bourg, et al. (2016), Brosset et al. (2017) also found a decrease in the size, weight and body condition of sardines in the North Western Mediterranean associated with an increase in the thermal stratification, reduction in the primary productivity of the waters and changes in the composition of the planktonic communities. All these works suggest a possible link between the SST positive trend and the negative trend of sardine landings in the northern Alboran Sea.

The existence of a positive trend in the SST and a negative one in the landings time series is not enough to establish a causal relationship for the landings decrease. Once the linear trends have been subtracted, the time series show the inter-annual variability and then the correlation could be analysed. In this case, there is a negative correlation between the SST and the sardine landings. It could be argued that warmer years produce a lower recruitment and then lower landings, while cooler years would have the opposite effect. In that case, an extending period of increasing temperatures could produce a decreasing trend in sardine abundance. Nevertheless, this argument also has some drawbacks. First, the SST was not one of the environmental variables that finally were included in the model that accounts for the sardine landings variability. Second, it has been hypothesized that the SST could affect sardine abundance through increased thermal stratification, lower rates of primary production and changes in the phyto- and zooplankton composition that would affect the condition of sardines (Brosset et al., 2015, 2017). This decrease in body condition was observed at the North Western Mediterranean, but not in the northern Alboran Sea (Brosset et al., 2017). Furthermore, chlorophyll time series showed a significant positive trend (Figure 3b and Table S2) from 1978 to 2017. A non-homogeneity was detected during the first three years, very likely associated with the use of the coastal zone color scanner (Figure S3a). If these years are eliminated from the analysis, the

resulting trend is not statistically significant. Nevertheless, it is still positive. According to these results, it cannot be established that the sea warming has caused a decrease in the primary production of the Alboran Sea associated with an increase in the thermal stratification. García-Martínez et al. (2018) and Vargas-Yáñez et al. (2019) did not find any negative trend for the mixed layer depth and the nutricline position in the northern Alboran Sea. These works considered that besides the fertilizing effect of wind mixing, whose efficiency could be reduced by the increase in thermal stratification, there are other mechanisms that enhance primary production in the Alboran Sea. Such mechanisms would not be affected by the sea warming and include cyclonic circulation cells, frontal zones and tidal mixing in the nearby Strait of Gibraltar. This would also explain that the reduction in body size and weight and body condition experienced by the sardine in the North Western Mediterranean did not affect the Alboran Sea.

The negative trend of sardine landings could be explained by the negative trend observed for the second principal component of the chlorophyll concentration. The spatial structure (EOF) associated with this PC is presented in Figure 6b and shows the out-of-phase variability of chlorophyll concentration at the northern Alboran coast, and to the south, in the inner part of the anticyclonic gyres. This PC is positively correlated to sardine landings (with a one-year time lag) and shows a negative trend, which is significant at the 0.1 significance level (see Table S2). Therefore, the long-term decrease experienced by this time series could be linked to the one observed for sardine landings.

Concerning the inter-annual variability of the sardine landings, the three variables included in the best approximating model were  $S(t-1)$ ,  $Chl\_A2(t-1)$  and  $V_m(t-1)$  (expression 1 and Tables 1 and 2). All these variables have a one-year time lag. This linear model is able to explain 79% of the sardine landings variance. If the negative linear trend existent in the sardine time series is taken into account, the explained variance increases to 86%. This model includes two variables associated with fertilizing processes during the preceding year:  $Chl\_A2(t-1)$  and  $V_m(t-1)$ . The second principal component is linked to the upwelling intensity in the northern Alboran coast. The wind intensity could also be associated with fertilizing processes by mixing of the water column. According to our results, recruits seem to incorporate to fisheries during summer and autumn when the landings reach maximum values. The hatching period for these recruits corresponds to the autumn season for the preceding year and the winter season of the same year. Therefore, the body condition of spawners would depend on the food availability during the preceding year. These facts indicate that the annual recruitment success is strongly dependent on the condition of spawners that in turn depends on the food availability during the preceding year. Besides this, it is important to remark that the dependence of sardine abundance on variables with a one-year lag and the possibility to predict such abundances one year in advance could have important implications for fisheries management.

In summary, the European sardine spawning period in the Alboran Sea extends from mid-autumn to late winter. Spawning

occurs at sea temperatures slightly higher than those reported for the Eastern North Atlantic and the nearby North Western Mediterranean. The spawning period is coincident with the period of highest primary production in the Alboran Sea. This high productivity is enhanced by wind-induced mixing and upwelling favoured by westerly winds. Other factors such as cyclonic gyres and frontal zones are also likely factors to induce high primary production rates in the northern Alboran Sea. Individuals hatched during autumn and winter are incorporated to the fishery during the following summer and autumn, producing the maximum annual sardine landings. Such landings fluctuate with a strong inter-annual variability that seems to be dependent on the food availability during the preceding year. Therefore, the condition of spawners seems to be the main factor controlling recruitment success. There is a long-term decrease in sardine landings. The main hypotheses to explain such decrease are the warming of seawaters and the decrease in the upwelling intensity inferred from empirical orthogonal function analysis. Nevertheless, these are still open questions that require further research. It should be noted that time series of chlorophyll concentrations averaged for the northern half of the Alboran Sea and the northern continental shelf do not show a significant decrease. The possibility of predicting sardine landings one year in advance could have important implications for fishery management.

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#### CONFLICT OF INTEREST

None of the authors have any conflict of interest.

#### AUTHOR CONTRIBUTION

A. Giráldez, P. Torres and M. González are responsible for the data collection, database management and the biological sampling. M. Vargas-Yáñez, M. C. García-Martínez and F-Moya are responsible for the statistical analyses and programming. All the authors contributed to the manuscript redaction.

#### DATA AVAILABILITY STATEMENT

Data are available under request.

#### ORCID

Manuel Vargas-Yáñez  <https://orcid.org/0000-0003-0456-9096>

Pedro Torres  <https://orcid.org/0000-0002-7076-6023>

María González  <https://orcid.org/0000-0003-4248-1765>

María del Carmen García-Martínez  <https://orcid.org/0000-0001-6526-9164>

<https://orcid.org/0000-0001-6526-9164>

Francina Moya  <https://orcid.org/0000-0001-9856-5234>

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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