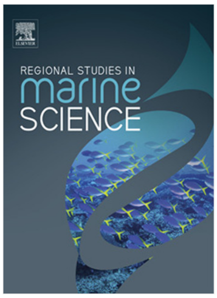

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Long term oscillations of Mediterranean sardine and anchovy explained by the combined effect of multiple regional and global climatic indices

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Short title: ENSO and PDO affect fisheries from Mediterranean

ABSTRACT

It is widely known that the abundance and distribution dynamics of populations of small pelagic clupeid fish, such as sardines and anchovies, are affected by large-scale climate variability, which may lead to changeovers to new regimes of small pelagics. However, long-distance climatic oscillations, such as El Niño/La Niña and the Pacific Decadal Oscillation, have been little explored in the Western Mediterranean Sea. We investigated the possible effects of the South Oscillation Index (i.e. the atmospheric oscillation coupled with the El Niño/La Niña) and Pacific Decadal Oscillation on fluctuations in catches of European anchovy (*Engraulis encrasicolus*) and sardine (*Sardina pilchardus*) in the Western Mediterranean Sea, and their association with regional climate oscillations (i.e. the Atlantic Multidecadal Oscillation, the North Atlantic Oscillation, the Western Mediterranean Oscillation index, and the Arctic Oscillation). The study covered two periods: a) landings between 1950 and 2016; and b) abundance, biomass, and physical condition (i.e., relative condition index) between 2004 and 2016. The main large-scale climatic oscillations in the region were studied using General Additive Models to investigate the relationship between a time series of species measures of European sardine and anchovy from Geographical Subarea 06. Results show that the long-term Pacific Decadal Oscillation favours sardine landings, whereas the combined effect of the Western Mediterranean Oscillation Index and the Atlantic Multidecadal Oscillation favours anchovy. We discuss potential links between the present findings and changes in the plankton community caused by prevailing winds in the region driven by long-distance climate oscillations and their impact on the reduction in small pelagic fish populations in the study area.

Keywords

Climatic oscillation, Asian Monsoon, ENSO, PDO, fisheries, small pelagic fish, SOI.

1. Introduction

It is widely known that the abundance and distribution dynamics of populations of small pelagic clupeoid fish, such as sardines and anchovies, are affected by large-scale climate oscillations (e.g., see Rykaczewski and Checkley, 2008; McClatchie, 2014; Báez et al., 2021). These climate indices are considered to represent "oscillations" of a dipole that drive changes in local weather trends.

Climate oscillations, or teleconnections, are the naturally reoccurring changes of normal weather patterns in a local area and are associated with the interactions of atmospheric and oceanic conditions. Among the most relevant climatic oscillations in the northern hemisphere are the Pacific Decadal Oscillation (PDO), the Atlantic Multidecadal Oscillation (AMO), the North Atlantic Oscillation (NAO), the Western Mediterranean Oscillation index (WeMOi), and the Arctic Oscillation (AO) (e.g., see Chávez et al., 2003; Martin-Vide and Lopez-Bustins, 2006; Báez and Real, 2011; Alheit et al., 2014; Báez et al., 2019; Báez et al., 2021). However, the associations between them have not yet been fully explained (Sutton and Hodso, 2003; Hurrel and Deser, 2009). In this line, Wang et al. (2014) found that the PDO and El Niño/La Niña combination could affect dry-wet patterns even in remote areas of the Pacific Ocean. They also reported that the effect of the El Niño-South Oscillation (ENSO) on dry-wet changes varies along with the PDO phase. When in phase with the PDO, ENSO-induced dry-wet changes are amplified in relation to the canonical pattern. When out of phase, these dry-wet variations weaken or even disappear (Wang et al., 2014). Therefore, different climatic oscillations could have combined and differential effects leading to locally differential climatic responses (e.g., Báez et al., 2013; Wang et al., 2014).

In this setting, the ENSO and the Southern Oscillation Index (SOI) (i.e. the atmospheric oscillation coupled with the ENSO) are the main source of global atmosphere-ocean variability patterns. It is widely accepted that they drive climatic variability in the Pacific Ocean and adjacent Indian Ocean (Yan et al., 2011; Wang et al., 2014; Wieners et al., 2017).

On the other hand, although climatic oscillations have a differential local response, this does not imply that they produce short-distance effects. Thus, the spatial manifestation of the corresponding effects depends on the magnitude of the different events (and combinations with other processes), and responses range from weak regionally confined trends to global large-scale teleconnectivity patterns (Lyon and Barnston, 2005; Lin and Qian, 2019; Kittel et al., 2021). Several authors have drawn attention to the relevance of tropical-extratropical ocean-atmosphere interactions on the North Atlantic and Mediterranean climate (Rogers, 1984; Sutton and Hodson, 2003; Hurrel and Deser, 2009; Losada et al., 2012; Stan et al., 2017).

Surprisingly, Hasanean (2004) found an association between the mean seasonal and annual precipitation in the Mediterranean region and the ENSO during the period 1951 to 1998. Using observational datasets and atmospheric reanalyses, Mariotti et al. (2002) showed that the interannual variability of rainfall in the Euro-Mediterranean sector is significantly influenced by the ENSO in a way that varies by season. Sánchez-Laulhé (2020) showed that there is a direct relationship between the development of La Niña conditions in the Tropical Pacific and the wind regime during the summer in the Western Mediterranean region. This relationship could be mediated by the Indian summer monsoon. Rodwell and Hoskins (2001) suggested that the warm-to-hot and very dry summers of Mediterranean-type climates were associated with adiabatic descents induced remotely by the monsoon to the east. The PDO can also influence the interannual variability of Indian Summer Monsoon (ISM) rainfall by strengthening the ENSO-ISM relationship when the ENSO and the PDO are in phase, while weakening the relationship when they are out of phase (Krishnamurthy and Krishnamurthy, 2013; Dong et al., 2018). Moreover, previous studies have also shown that the El Niño event affects planktonic communities in the Western Mediterranean Sea (Hernández-Almeida et al., 2005, 2011).

Based on the foregoing, the current study investigates the possible long-distance effect of major world climate oscillations (i.e., the PDO and SOI) and local climate oscillations (i.e. AMO, AO, NAO, and WeMOi) on stocks of European anchovy (*Engraulis encrasicolus*) and sardine (*Sardina pilchardus*) in the Western Mediterranean Sea. This area can respond quickly to any such effects. Understanding the response of small pelagic fish to great climate variability over long-term periods is relevant to forecasting human-induced responses to climate change.

Material and Methods

Fisheries data

The main challenge in analysing biological processes in oceans over long-term periods is the general lack of available time series of oceanographic studies and data on the physical condition of fish. However, the use of landing data can be used as a proxy for fish abundance (for example Castro-Gutiérrez et al., 2022). Nevertheless, the use of such data can be controversial, because they include fleet variability and technical improvements, and can also miss unreported catches (Pauly et al., 2013). Nevertheless, according to Pauly et al. (2013), landings are very often the best data available and have been used by the FAO and Fisheries Management Regional Organization for stock assessments. Thus, it is reasonable to use them as a proxy for abundance, or at least regarding abundance trends over time. To address this issue, we studied two sets of data with different time scales. On the one hand, as a proxy for abundance, we used the sardine and anchovy landings in subarea GSA06 (General Fisheries Commission for the Mediterranean) (Figure 1) from 1950 to 2016. On the other hand, we also analysed direct estimates of biomass, abundance, and physical condition per species annually between 2003 and 2016, as data were available for this period.

Specifically, the landing database of European anchovy and sardine from the GSA06 (from the French border to the Cape of Gata) (Figure 1) was built using annual time series provided by different national authorities (i.e. Spanish Fisheries Authorities, the Spanish Autonomous Communities, and own data of the Instituto Español de Oceanografía: further details on the time series can be found in Abad and Giráldez, 1990; Abad et al., 1991; Giráldez and Abad, 1991, 2000, and Giráldez and Alemany, 2002).

For the period 2003 to 2016, we used the data from the Spanish Acoustic Survey "Eco-MEDiterranean" (ECOMED) (2003 to 2008) and the EUfunded MEDIterranean International Acoustic Survey (MEDIAS) (2009 to 2016). The following data were obtained from the aforementioned oceanographic surveys: biomass (metric tons), abundance (number of individuals), relative condition index (Kn; Le Cren, 1951) (Brosset et al., 2016; Albo-Puigserver et al., 2020; Pennino et al., 2020, Baez et al., 2021). Further details on the performance of these anchovy and sardine biological variables can be consulted in previous studies (Pennino et al., 2020; Baez et al., 2021).

Large-scale climate data

We studied the NAO, AO, AMO, and WeMOi, which are the main drivers of climatic variability in the northern hemisphere regional area. We also studied the SOI and PDO, which are main global climatic oscillations. The WeMOi values were obtained from the University of Barcelona Climatology Group (http://www.ub.edu/gc/es/WeMOi/) and the PDO index used was the classic estimation proposed by Mantua et al. (1997) (http://research.jisao.washington.edu/pdo/PDO.latest.txt: accessed: 18/04/2021). Data on the other climatic oscillations were obtained from the National Oceanic and Atmospheric Administration of USA website.

Generalized Additive Models

Generalized Additive Models (GAMs) were used to investigate the effect of the climate oscillation indices on the species variables (i.e., landings, abundance, biomass, and Kn). The main advantage of GAMs is that they are a non-parametric generalization of multiple linear regressions and have less restrictive assumptions regarding the underlying statistical data distributions (Hastie and Tibshirani 1990). GAMs use data-driven functions, such as splines and local regression, which have superior performance relative to the polynomial functions used in linear models (Zwolinski et al., 2011; Diankha and Thiaw, 2016). Specifically, for each species and dependent variable, GAMs with a Gaussian distribution were applied after the response variables had been log transformed.

Prior to performing the GAMs, we used a standard technique—in this case, a Pearson's correlation test with the *corrplot* package (Wei and Simko, 2017)—to identify possible correlations between the explanatory variables. Pairs of variables with high correlation values (Pearson's correlation > 0.7) were identified. In particular, a high correlation was found between the AO and NAO ($r > 0.70$) and thus the AO was excluded from further analysis (Supplementary Materials, Figure S1).

In addition to the climate oscillation indices, the year was included as a continuous variable in all the GAMs in order to assess unexplained temporal variability. Semi-parametric smooth functions (s) were used to fit the interactions between the climatic indices and each of the fish species variables, restricting the dimension of the basis (k) to 4 in order to allow a high degree of flexibility while avoiding overfitting problems (for example Lloret-Lloret et al., 2022).

After a stepwise forward procedure, the best final model was selected according to the lowest Akaike Information Criterion (AIC) and the highest adjusted R-square. For each final GAM, the assumptions of the model were determined by testing on residuals the theoretical assumptions of normality, homoscedasticity, and independence. Temporal correlations in the residuals were determined using the autocorrelation (ACF) and partial (PACF) functions (Wood, 2006).

Data exploration and statistical analyses were conducted with R 4.0.3 (R Core Team, 2020). The GAMs were analysed using the *mgcv* library (version 1.8, Wood and Wood, 2015) in R.

Results

Landings (1950-2016)

For sardine landings (1950-2016), the only significant variables in the final model were the Pacific Decadal Oscillation (PDO) and the unexplained annual trend. This model explained 79% of the variability in sardine landings. Specifically, a positive association was found between the PDO and sardine landings, while the year effect shows that although there was an increase in landings in the 1980s and 1990s, landings decreased from 2000 onward (Figure 2).

The anchovy landings model retained as significant predictors the Atlantic Multidecadal Oscillation (AMO) and Western Mediterranean Oscillation (WeMOi) indices as well as the unexplained annual trend. For these variables two opposite relationships were found with respect anchovy landings, negative for the AMO and positive for the WeMOi and the year. Overall, these predictors explained 53% of the variability in anchovy landings (Figure 3).

Biomass, abundance, and physical condition (2004-2016)

Results of the sardine biomass model highlighted that all the variables were significant, except for the unexplained annual trend. This model explained 78% of the total data variability. Specifically, a positive association was found between the North Atlantic Oscillation (NAO) and Atlantic Multidecadal Oscillation (AMO) indices and the sardine biomass, whereas a negative association was found between the PDO, WeMOi, and SOI and the sardine biomass (Figure 4). On the contrary the anchovy biomass model retained only the annual trend that alone explained 76% of the variability of the data (Figure 5).

For the sardine abundance, the majority of the variability (49%) was explained by the WeMOi and unexplained annual trend (Figure 6). Both variables showed a negative association with the abundance of sardine.

The unexplained annual trend was also a final predictor in the anchovy abundance model, jointly with the PDO. Both variables showed slightly significant positive associations with the anchovy abundance (Figure 7) and explained 57% of the variability.

For sardine Kn, the final model explained 64% of the variability. The retained significant predictors were the NAO and WeMOi indices. A dome-shaped association was found between the NAO and sardine Kn, whereas a mixed association was found between the WeMOi index and sardine Kn (Figure 8). Finally, in the GAM for anchovy Kn, significant positive associations were only found between the Southern Oscillation Index (SOI) and the AMO indices and anchovy Kn. Both variables jointly explained 93% of the variability in anchovy Kn (Figure 9).

For all GAM analyses, the residuals show the absence of any violations and temporal autocorrelations (see Supplementary Materials, Figures S2 to S17).

Table 1 shows the main results of the GAM analysis in relation to landings, abundance, biomass, and physical condition (Kn) by species.

Discussion

Alheit et al. (2014) demonstrated that, over the long-term, sardine and anchovy from the European Atlantic and Mediterranean coasts respond to the Atlantic Multidecadal Oscillation. In this line, Báez et al. (2022) found that, over the short-term, there is a positive association between sardine landings and the Atlantic Multidecadal Oscillation, whereas this association is negative in the case of anchovies. They also found positive associations between sardine biomass and the Atlantic Multidecadal Oscillation and between anchovy biomass and physical condition. Alheit et al. (2014) also observed that, since the mid-1990s, increases in the abundance and spatial occupation of European anchovy in the North Sea have been related to the Atlantic Multidecadal Oscillation, whereas from 2012 to 2022, there has been a strong decreasing trend in sardine landings in the Western Mediterranean Sea (Quattrocchi and Maynou, 2017; Coll et al., 2019; Báez et al., 2022). Our findings were similar to those of Alheit et al. (2014) in the case of anchovy from the Western Mediterranean Sea over the long term. However, we found a long-term association between sardine and the Pacific Decadal Oscillation (PDO). In effect, and as highlighted by Alheit et al. (2014), the period from 1992 to 1998 corresponds to a positive PDO phase with the highest average landings (i.e. 43978 t). In contrast, the period between 2007 and 2013 corresponds to a negative PDO phase with the lowest average landings (13120.4 t).

In the short term, there could be an association between the PDO and sardine biomass and anchovy abundance, and an association between the Southern Oscillation Index (SOI) and the physical condition of anchovy. As these findings refer to the short term, they should be taken with caution: further research is needed using longer data series. Fortunately, we were able to make use of a 67-year period of sardine and anchovy landings to test our hypothesis. Nevertheless, we are aware that this period is not homogeneous in relation to fishing characteristics because there have been significant technical advances over this period as well as changes in the catch composition of the fleet that could distort the results. However, the results show a clear association between the PDO and sardine, and, to a lesser extent, between the PDO and anchovy.

A possible explanation for the distant effect of the PDO on fluctuations of sardine and anchovy could be related to rain patterns and wind regimes in the Mediterranean region due to the Asian monsoon, which in turn is driven by the PDO/SOI. Rykaczewski and Checkley (2008) showed that increases in the level of wind-stress curl and SST affected the production of Pacific sardine *Sardinops sagax*. They also showed that the wind-stress curl has oscillated over the past 6 decades and that it is positively correlated with the extent of isopycnal shoaling, nutricline depth, and chlorophyll concentration. Likewise, wind regimes over the Mediterranean Sea driven by the PDO/SOI could have a similar effect. Previous studies have also shown that the El Niño event affects planktonic communities in the Western Mediterranean Sea (Hernández-Almeida et al., 2005, 2011).

Thus, there is a connection between long-distance wind regimes and changes in plankton communities. In turn, it has been observed that there is a differential trophic gradient in anchovy and sardine in the Western Mediterranean Sea, which is due to the differential community plankton composition (Bachiller et al., 2020). Moreover, Brosset et al. (2016) suggested that there is an association between small pelagic dietary shifts and ecosystem changes in the Gulf of Lion. Finally, it has been shown that rain patterns in the Mediterranean region increase the productivity of the sea (Macías et al., 2015), which could alter trophic gradients.

A key finding of the present study is that the combined effect of multiple regional and global climatic oscillations provides the best explanation of variability in anchovy and sardine abundance. Similar associations have been observed in other sites worldwide (Chavez et al., 2003; Checkley et al., 2017).

As argued by Báez et al. (2021), although there are many climatic oscillations, there is only a single atmosphere (i.e. climate on a global scale is interconnected by so-called atmospheric bridges or teleconnections). The PDO has also been shown to have remote associations with multi-decadal drought and pluvial conditions over many distant areas through atmospheric teleconnections (Zanchettin et al., 2008; Wang et al., 2009; Wang et al., 2014; Vance et al., 2015; Johnson et al., 2020) and marine biological process (Mantua et al., 1997; Mantua and Hare, 2002; Chavez et al., 2003; Báez et al., 2020). There are inter-basin atmosphere-ocean interactions from the Atlantic to the North Pacific and *vice versa*, such as the Arctic Oscillation interaction (mediated by the Sea Surface Temperature in the North Atlantic) or the Atlantic Multidecadal Oscillation, which influences the PDO in such a way that it affects the wet/dry patterns in the Atlantic region (Johnson et al., 2020). Thus, in combination with other climatic oscillations, the PDO can be considered to be a good proxy for both the regional and global variability that affects the regional climate of the Western Mediterranean. The fact that the response of ecosystems can be better explained by distant climatic oscillations than by local physical variables is a paradox that has been previously described (Stenseth et al., 2003; Hallett et al., 2004; Báez et al., 2021). Stenseth et al. (2003) suggested that climatic oscillations affect multiple weather variables simultaneously—sometimes in distant areas—in what they called packages of weather, thus affecting the response of corresponding ecosystems (Stenseth et al., 2003; Hallett et al., 2004; Bastos et al., 2016).

On the other hand, the Western Mediterranean Oscillation index could have a relevant impact at a regional scale (Martin-Vide and Lopez-Bustins, 2006), at least in the case of anchovy. Martin et al. (2012) found that the Western Mediterranean

Oscillation index affected sardine and anchovy populations. We found that the Western Mediterranean Oscillation index had an effect on anchovy biomass.

The North Atlantic Oscillation is the largest source of interannual variability in the Northern Hemisphere and is related to the multiple biological responses of many fish stocks (for a recent review, see Báez et al., 2021). However, the North Atlantic Oscillation was not included in all of the final models. In fact, according to Martin-Vide and Lopez-Bustins (2006), due to the orography and geographic position of the Western Mediterranean area, climatic variability could be better captured by the WeMOi than by the North Atlantic Oscillation. Nevertheless, according our results there is an unimodal relationship between the North Atlantic Oscillation and sardine Kn (Figure 8). The North Atlantic Oscillation reflects the difference in atmospheric pressure at sea level between the Icelandic low and the high over the Azores archipelago. It is therefore a difference between pressures, and can take positive or negative signs. However, values close to zero are a mild North Atlantic Oscillation. In fact, as reviewed in Báez et al. (2021) the extreme values of the North Atlantic Oscillation, are the most important. Therefore, the inverted U-shaped effect on sardine Kn could respond, on the one hand, to a worsening of sardine feeding due to an extreme value (positive or negative phase), and on the other hand, to an increased competitive stress due to an extreme value of the NAO variable (positive or negative phase).

Regarding the Arctic Oscillation index, the Arctic Oscillation is another relevant climatic oscillation in the Northern Hemisphere and is strongly correlated with the North Atlantic Oscillation, which itself depends on the strength of the polar vortex (Báez et al., 2013). A relationship has been found between the Arctic Oscillation and Catch per Unit of Effort of sardine in the purse seine fisheries in Northwest Africa (Báez et al., 2019).

In recent decades, there have been relevant changes in small pelagic fish populations in the North Western Mediterranean Sea. The most noticeable fluctuations in these important fishery resources have been declines in landings, biomass, abundance sardine. According to Coll et al. (2019), these changes could have multiple causes, including the cumulative effect of environmental change, overfishing, competition for trophic resources, and predation. However, we would like to highlight the fact that positive PDO phases could significantly explain trends in sardine and anchovy landings. Unfortunately, we are currently in a negative PDO phase, which could aggravate the reduced sardine stocks in the Western Mediterranean.

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Conflicts of Interest

None declared.

Author Contributions

Conception and methodology design: JCB; data collection: JCB, MGP, AG, CGS; data analysis: MGP, IAC, CGS; first draft: JCB and MGP. All authors critically reviewed the drafts and gave final approval for publication.

Ethical Statement

No specific authorization was required for any of the activities undertaken during this study, which was conducted using statistical fishery data available online.

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References

Abad, R., Giráldez, A., 1990. Descripción de la pesca de cerco en la Región Surmediterránea. Inf. Téc. Inst. Esp. Oceanogr. 86, 1-48. Available from the bibliographic repository of the Spanish Institute of Oceanography, http://www.repositorio.ieo.es/e-ieo/

Abad, R., Giráldez, A., De Carranza, I., 1991. Series históricas de desembarcos en el Mediterráneo español, FAO. Rapp. Pêches 447, 171-191. Available from the bibliographic repository of the Spanish Institute of Oceanography, http://www.repositorio.ieo.es/e-ieo/

Albo-Puigserver, M., Sánchez, S., Coll, M., Bernal, M., Sáez-Liante, R., Navarro, J., Palomera, I., 2020. Year-round energy dynamics of sardine and anchovy in the north-western Mediterranean Sea. Mar. Environ. Res. 159, 105021.

Alheit, J., Licandro, P., Coombs, S., García, A., Giráldez, A., Santamaría, M.T.G., Slotte, A., Tsikliras, A.C., 2014. Atlantic Multidecadal Oscillation (AMO) modulates dynamics of small pelagic fishes and ecosystem regime shifts in the eastern North and Central Atlantic. J. Mar. Syst. 133, 88-102.

Báez, J.C., Czerwinski, I.A., Ramos, M.L., 2020. Climatic oscillations effect on the yellowfin tuna (*Thunnus albacares*) Spanish captures in the Indian Ocean. Fish. Oceanogr. 29, 572-583.

Báez, J.C., Gimeno, L., Gómez-Gesteira, M., Ferri-Yáñez, F., Real, R., 2013. Combined effects of the North Atlantic Oscillation and the Arctic Oscillation on Sea Surface Temperature in the Alborán Sea. PLoS ONE 8(4), e62201. https://doi.org/10.1371/journal.pone.0062201.

Báez, J.C., Gimeno, L., Real, R., 2021. North Atlantic Oscillation and fisheries management during global climate change. Rev. Fish. Biol. Fish. 31, 319–336. https://doi.org/10.1007/s11160-021-09645-z.(

Báez, J.C., Pennino, M.G., Albo-Puigserver, M., Coll, M., Giraldez, A., Bellido, J.M., 2022. Effects of environmental conditions and jellyfish blooms on small pelagic fish and fisheries from the Western Mediterranean Sea. Estuar. Coast. Shelf. Sci. 264, 107699. https://doi.org/10.1016/j.ecss.2021.107699

Báez, J.C., Real, R., 2011. The North Atlantic Oscillation affects the landings of Anchovy *Engraulis encrasicolus* in the Gulf of Cádiz (South of Spain). J. Appl. Ichthyol. 27, 1232–1235.

Báez, J.C., Santamaría, M.T.G., García, A., González, J.F., Hernández, E., Ferri-Yáñez, F., 2019. Influence of the Arctic Oscillations on the sardine off northwest Africa during the period 1976/1996. Vie Milieu 69(1), 71-77.

Bachiller, E., Albo-Puigserver, M., Gimenez Verdugo, J., Grazia Pennino, M., Mari-Mena, N., Esteban, A., Lloret Lloret, E., Jadaud, A., Carro, B., Bellido, J.M., Coll, M., 2020. A trophic latitudinal gradient revealed in anchovy and sardine from the Western Mediterranean Sea using a multi-proxy approach. Sci. Rep. 10, 17598. https://doi.org/10.1038/s41598-020-74602-y

Bastos, A., Janssens, I.A., Gouveia, C.M., Trigo, R.M., Ciais, P., Chevallier, F., Peñuelas, J., Rödenbeck, C., Piao, S., Fridlingsteis, P., Running, S.W., 2016. European land CO_2 sink influenced by NAO and East-Atlantic pattern coupling. Nat. Commun. 7, 10315. https://doi.org/10.1038/ncomms10315

Brosset, P., Le Bourg, B., Costalago, D., Bănaru, D., Van Beveren, E., Bourdeix, J.H., Fromentin, J.M., Ménard, F., Saraux, C., 2016. Linking small pelagic dietary shifts with ecosystem changes in the Gulf of Lions. Mar. Ecol. Progr. Ser. 554, 157-171.

Castro-Gutiérrez, J., Cabrera-Castro, R., Czerwinski, I.A. et al. Effect of climatic oscillations on small pelagic fisheries and its economic profit in the Gulf of Cadiz. Int J Biometeorol 66, 613–626 (2022). https://doi.org/10.1007/s00484-021-02223-9

Chávez, F.P., Ryan, J., Lluch-Cota, S.E., Niquen, M., 2003. From anchovies to sardines and back: multidecadal change in the Pacific Ocean. Science 299, 217-221.

Checkley, D.M., Asch, R.G., Rykaczewski, R.R., 2017. Climate, Anchovy, and Sardine. Annu. Rev. Mar. Sci. 9, 469-493.

Coll, M., Albo-Puigserver, M., Navarro, J., Palomera, I., Dambacher, J., 2019. Who is to blame? Plausible pressures on small pelagic fish population changes in the NW Mediterranean Sea. Mar. Ecol. Progr. Ser. 617-618, 277-294.

Diankha, O., Thiaw, M., 2016. Studying the ten years variability of *Octopus vulgaris* in Senegalese waters using generalized additive model (GAM). Int. J. Fish. Aquat. 4(3), 61-67.

Dong, B., Dai, A., Vuille, M., Timm, O.E., 2018. Asymmetric modulation of ENSO teleconnections by the interdecadal Pacific oscillation. J. Climate 31, 7337–7361. https://doi.org/10.1175/JCLI-D-17-0663.1.

Giráldez, A., Alemany, F., 2002. The small pelagic fisheries in the South-Mediterranean Region (Western Mediterranean Sea): Past and present state. GFCM-SAC-Subcommittee of Stock Assesment Working Group on Small Pelagic especies Rome, Italy, 20-22 March, 2002. Available from the bibliographic repository of the Spanish Institute of Oceanography, http://www.repositorio.ieo.es/e-ieo/

Giráldez, A., Abad, R., 1991. La pesquería de cerco en la Región Surmediterránea en 1989-1990. Inf. Téc. Inst. Esp. Oceanogr. 105, 1-31. Available from the bibliographic repository of the Spanish Institute of Oceanography, http://www.repositorio.ieo.es/e-ieo/

Giráldez, A., Abad, R., 2000. Serie histórica de capturas de los pequeños pelágicos en el Mediterráneo español (1945–1997) y capturas, esfuerzos y flota de cerco de la Región Surmediterránea. Datos y Resúmenes Datos y Resúmenes Instituto Español de Oceanografía 13: 1-26. Available from the bibliographic repository of the Spanish Institute of Oceanography, http://www.repositorio.ieo.es/e-ieo/

Hallett, T.B., Coulson, T., Pilkington, J.G., Clutton-Brock, T.H., Pemberton, J.M., Grenfell, B.T., 2004. Why large-scale climate indices seem to predict ecological processes better than local weather. Nature 430, 71–75.

Hasanean, H., 2004. Precipitation variability over the Mediterranean and its linkage with El Nino Southern Oscillation (ENSO). J. Meteorol. 29, 151-160.

Hastie, T., Tibshirani, R., 1990. Exploring the nature of covariate effects in the proportional hazards model. Biometrics, 1005-1016.

Hernández-Almeida, I., Bárcena, M.A., Sierro, F.J., Flores, J.A., Calafat, A., 2005. Influence of 1997-98’ El Niño event on the planktonic communities from The Alboran Sea (Western Mediterranean). Geogaceta 38, 183-186.

Hernández-Almeida, I., Bárcena, M.A., Flores, J.A., Sierro, F.J., Sanchez-Vidal, A., Calafat, A., 2011. Microplankton response to environmental conditions in the Alboran Sea (Western Mediterranean): One year sediment trap record. Mar Micropaleontol 78:14-24.

Hurrell, J.W., Deser, C., 2009. North Atlantic climate variability: the role of the North Atlantic Oscillation. J. Marine Syst. 78(1), 28–41.

Johnson, Z.F., Chikamoto, Y., Wang, S.Y.S., McPhaden, M.J., Mochizuki, T., 2020. Pacific decadal oscillation remotely forced by the equatorial Pacific and the Atlantic Oceans. Clim. Dyn. 55, 789–811. https://doi.org/10.1007/s00382-020-05295-2

Kittel, T., Ciemer, C., Lotfi, N., Peron, T., Rodrigues, F., Kurths, J., Donner, R.V., 2021. Evolving climate network perspectives on global surface air temperature effects of ENSO and strong volcanic eruptions. Eur. Phys. J. Spec. Top. 230, 3075–3100.

Krishnamurthy, L., Krishnamurthy, V., 2013. Influence of PDO on South Asian summer monsoon and monsoon–ENSO relation. Clim. Dyn. 42, 2397–2410. https://doi.org/10.1007/s00382-013-1856-z.

Le Cren, E.D., 1951. The length-weight relationship and seasonal cycle in gonad weight and condition in the perch (Perca fluviatilis). J. Anim. Ecol. 20, 201–219.

Lin, J., Qian, T.A., 2019. New Picture of the Global Impacts of El Nino-Southern Oscillation. Sci. Rep. 9, 17543. https://doi.org/10.1038/s41598-019-54090-5.

Lloret-Lloret, E., Albo-Puigserver, M., Giménez, J., Navarro, J., Pennino, M.G., Steenbeek, J., Bellido, J.M., Coll, M., 2022. Small pelagic fish fitness relates to local environmental conditions and trophic variables. Prog. Oceanogr. 202, 102745.

Losada, T., Rodríguez-Fonseca, B., Kucharski, F., 2012. Tropical influence on the summer Mediterranean climate. Atmos. Sci. Lett. 13, 36–42. https://doi.org/10.1002/asl.359

Lyon, B., Barnston, A.G., 2005. ENSO and the spatial extent of interannual precipitation extremes in tropical land areas. J. Climate 18, 5095-5109.

Macias, D.M., Garcia-Gorriz, E., Stips, A., 2015. Productivity changes in the Mediterranean Sea for the twenty-first century in response to changes in the regional atmospheric forcing. Front. Mar. Sci. 2, 79. https://doi: 10.3389/fmars.2015.00079

Mantua, N.J., Hare, S.R., 2002. The pacific decadal oscillation. J. Oceanogr. 58, 35–44

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., Francis, R.C., 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bull. Amer. Meteor. 78, 1069–1079. https://doi.org/10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2.

Mariotti, A., Zeng, N., Lau, W., 2002. Euro-Mediterranean rainfall and ENSO- A seasonally varying relationship. Geophys. Res. Lett. 29. https://doi.org/10.1029/2001GL014248.

Martin, P., Sabatés, A., Lloret, J., Martin-Vide, J., 2012. Climate modulation of fish populations: the role of the Western Mediterranean Oscillation (WeMOi) in sardine (*Sardina pilchardus*) and anchovy (*Engraulis encrasicolus*) production in the north-western Mediterranean. Clim. Change 110, 925–939.

Martin-Vide, J., Lopez-Bustins, J. 2006. The Western Mediterranean Oscillation and Rainfall in the Iberian Peninsula. Int. J. Climatol. 26(11), 1455-1475

McClatchie, S., 2014. Regional Fisheries Oceanography of the California Current System: The CalCOFI program. Netherland: Springer

Pauly, D., Hilborn, R., Branch, T., 2013. Fisheries: Does catch reflect abundance?. Nature 494, 303–306. https://doi.org/10.1038/494303a.

Pennino, M.G., Coll, M., Albo-Puigserver, M., Fernandez-Corredor, E., Steenbeek, J., Giráldez, A., González, M., Esteban, A., Bellido, J.M., 2020. Current and future influence of environmental factors on small pelagic fish distributions in the Northwestern Mediterranean Sea. Front. Mar. Sci. 7, 622. https://doi.org/10.3389/fmars.2020.00622.

Quattrocchi, F., Maynou, F., 2017. Environmental drivers of sardine (Sardina pilchardus) in the Catalan Sea (NW Mediterranean Sea). Mar. Biol. Res. 13(9), 1003-1014.

R Core Team, 2020. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Rodwell, M., Hoskins, B., 2001. Subtropical Anticyclones and Summer Monsoons. J. Climate 14, 3192-3211. https://doi.org/10.1175/1520-0442(2001)014<3192:SAASM>2.0.CO;2.

Rogers, J.C., 1984. The association between the North Atlantic Oscillation and the Southern Oscillation in the Northern Hemisphere. Mon. Weather Rev. 112, 1999–2015.

Rykaczewski, R.R., Checkley, Jr. D.M., 2008. Influence of ocean winds on the pelagic ecosystem in upwelling regions. Proc. Natl. Acad. Sci. U.S.A. 105(6), 1965-1970. https://doi.org/10.1073/pnas.0711777105

Sánchez-Laulhé, J.M., 2020. El monzón y el clima de España en julio de 2020. Tiempo y Clima 70, 14-17

Stan, C., Straus, D.M., Frederiksen, J.S., Lin, H., Maloney, E.D., Schumacher, C., 2017. Review of tropical-extratropical teleconnections on intraseasonal time scales. Rev. Geophys. 55, 902–937. https://doi.org/10.1002/2016RG000538

Stenseth, N.C., Ottersen, G., Hurrell, J.W., Mysterud, A., Lima, M., Chan, K.S., Yoccoz, N.G., Ådlandsvik, B., 2003. Studying climate effects on ecology through the use of climate indices, the North Atlantic Oscillation, El Niño Southern Oscillation and beyond. Proc. Royal Soc. 270, 2087–2096. https://doi.org/10.1098/rspb.2003.2415.

Sutton, R.T., Hodson, D.L.R., 2003. Influence of the ocean on North Atlantic climate variability 1871-1999. Climate 16, 3296-3313.

Vance, T., Roberts, J., Plummer, C., Kiem, A., Van Ommen, T., 2015. Interdecadal pacific variability and eastern australian megadroughts over the last millennium. Geophys. Res. Lett. 42(1), 129–137.

Wang, S., Huang, J., He, Y., Guan, Y., 2014. Combined effects of the Pacific Decadal Oscillation and El Niño-Southern Oscillation on Global Land Dry-Wet Changes. Sci. Rep. 4, 6651. https://doi.org/10.1038/srep06651

Wang, S.Y., Gillies, R.R., Jin, J., Hipps, L.E., 2009. Recent rainfall cycle in the intermountain region as a quadrature amplitude modulation from the pacific decadal oscillation. Geophys. Res. Lett. 36(2), L02705. https://doi.org/10.1029/2008GL036329

Wei, T., Simko, V., Levy, M., Xie, Y., Jin, Y., Zemla, J., 2017. Package 'corrplot'. Statistician 56(316), e24.

Wieners, C.E., Dijkstra, H.A., de Ruijter, W.P.M., 2017. The Influence of Atmospheric Convection on the Interaction between the Indian Ocean and ENSO. J. Clim. 30(24), 10155–10178. https://doi.org/10.1175/JCLI-D-17-0081.1.

Wood, S., 2006. Generalized Additive Models: An Introduction with R. Chapman & Hall/CRC, Boca Raton, Florida

Wood, S., Wood, M.S., 2015. Package 'mgcv'. R package version, 1, 29.

Yan, H., Sun, L., Yuhong, W., Wen, H., Shican, Q., Chengyun, Y., 2011. A record of the Southern Oscillation Index for the past 2,000 years from precipitation proxies. Nature Geosci. 4, 611–614. https://doi.org/10.1038/ngeo1231

Zanchettin, D., Franks, S.W., Traverso, P., Tomasino, M., 2008. On ENSO impacts on European wintertime rainfalls and their modulation by the NAO and the pacific multi-decadal variability described through the PDO index. Int. J. Climatol. 28(8), 995–1006.

Zwolinski, J.P., Emmett, R.L., Demer, D.A., 2011. Predicting habitat to optimize sampling of Pacific sardine (*Sardinops sagax*). ICES Mar. Sci. 68(5), 867-879.

Table 1. Results of the GAM analysis of landings, abundance, biomass, and physical condition (Kn) by species.

	Landings	Abundance	Biomass	Kn
Sardine	PDO, Annual Trend (79%)	WeMOi (49%)	NAO, AMO, PDO, WeMOi, SOI (78%)	NAO, WeMOi (64%)
Anchovy	AMO, WeMOi, Annual Trend (53%)	PDO, Annual Trend (57%)	Annual Trend (78%)	SOI, AMO (93%)

Note: Explained variability is shown in parentheses for each case.
Abbreviations: PDO, Pacific Decadal Oscillation; SOI, South Oscillation Index; AMO, Atlantic Multidecadal Oscillation; WeMOi, Western Mediterranean Oscillation index; NAO, North Atlantic Oscillation.

FIGURE CAPTIONS

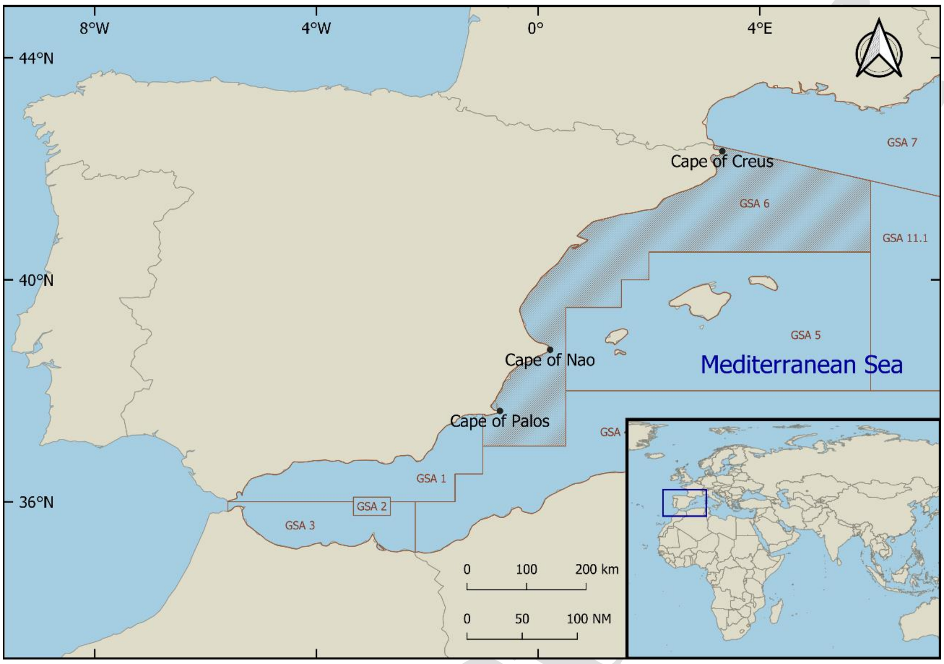

Figure 1: Map of the study area. The limits of the old national fishing regions have been highlighted on the map: Tramontana (between the Cape of Creus and the Cape of Nao) and Levante (between the Cape of Nao and Cape of Palos) and subarea GSA06 (General Fisheries Commission for the Mediterranean).

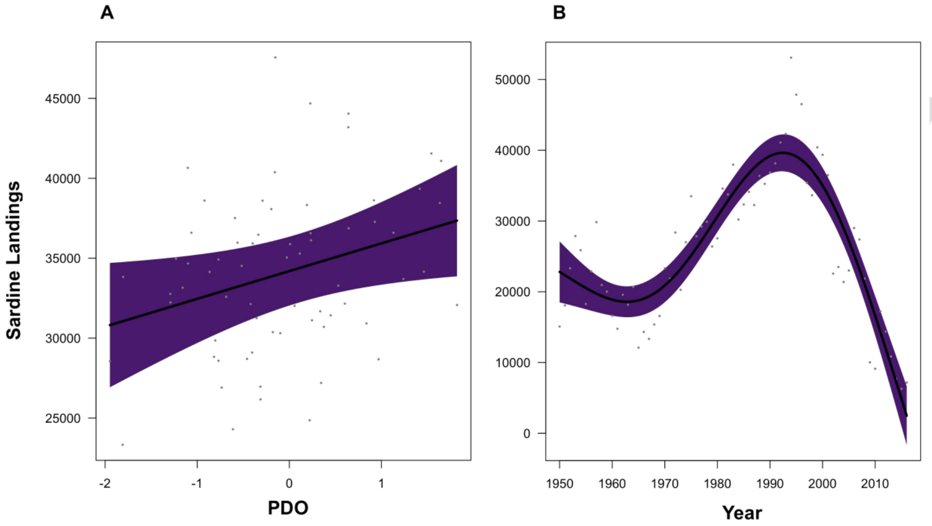

Figure 2: Partial GAM plots of sardine (*Sardina pilchardus*) landings (in tons). Significant partial effects of the (A) Pacific Decadal Oscillation (PDO), and (B) the year effect are shown. The shaded areas indicate the 95% confidence interval.

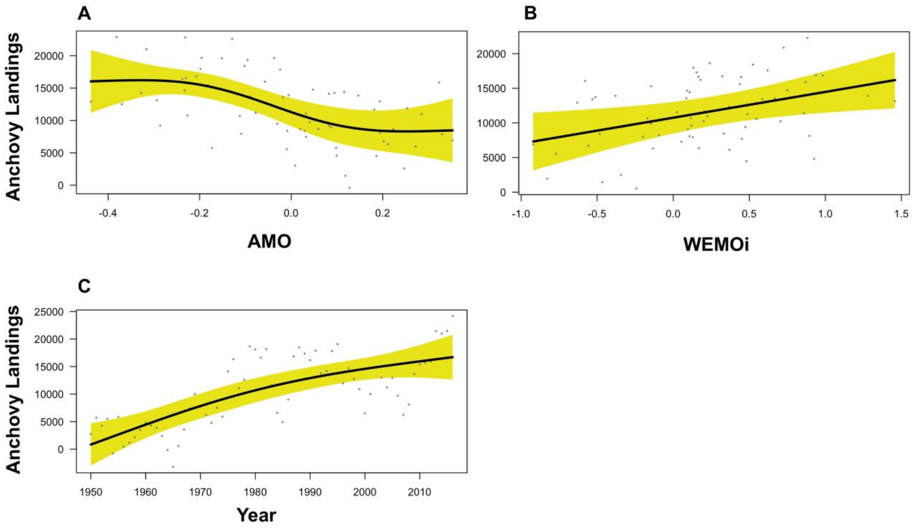

Figure 3: Partial GAM plots of anchovy (*Engraulis encrasicolus*) landings (in tons). Significant partial effects of the (A) Atlantic Multidecadal Oscillation (AMO), (B) Western Mediterranean Oscillation index (WEMO index) and the (C) year effect are shown. The shaded areas indicate the 95% confidence interval.

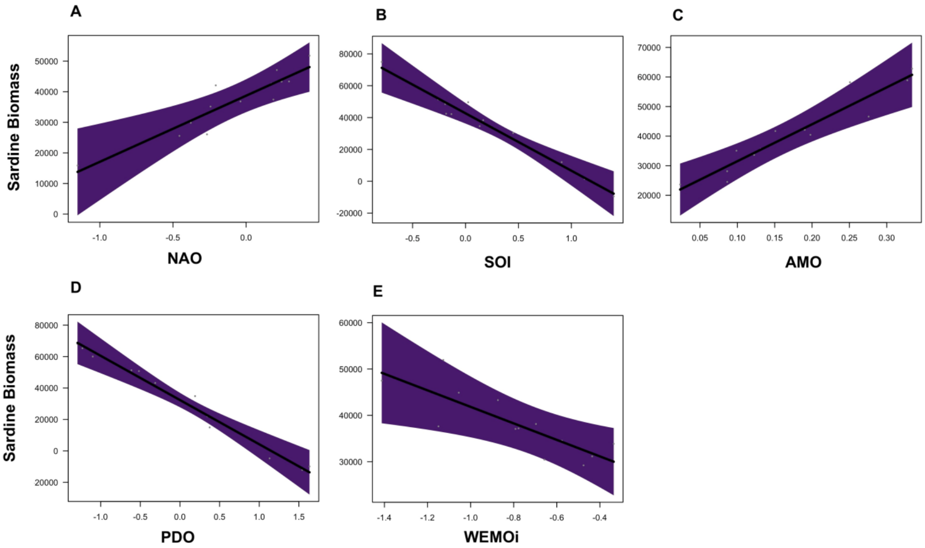

Figure 4: Partial GAM plots of sardine (*Sardina pilchardus*) biomass. (A) North Atlantic Oscillation (NAO), (B) Southern Oscillation Index (SOI), (C) Atlantic Multidecadal Oscillation (AMO), (D) Pacific Decadal Oscillation (PDO) and (E) Western Mediterranean Oscillation index (WEMO index). Significant partial effects of the explicative variables are shown. The shaded areas indicate the 95% confidence interval.

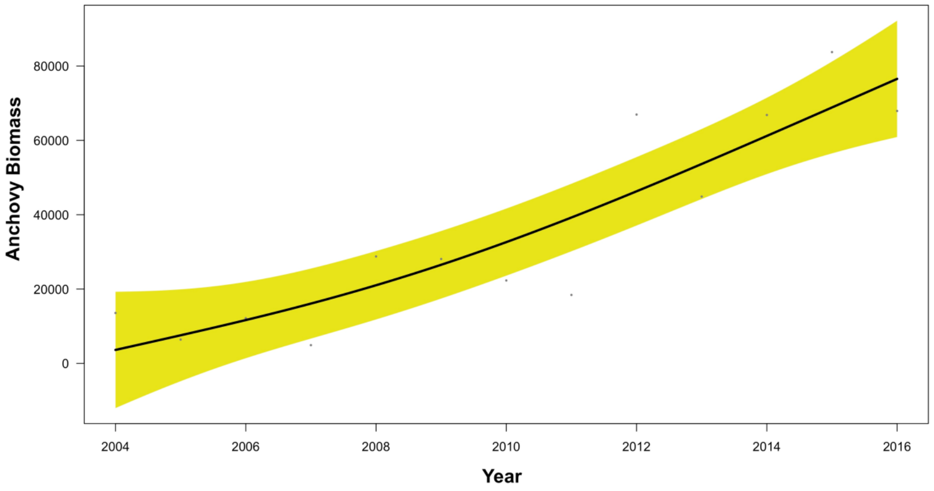

Figure 5: Partial GAM plots of anchovy (*Engraulis encrasicolus*) biomass. Significant partial effects of the year effect are shown. The shaded areas indicate the 95% confidence interval.

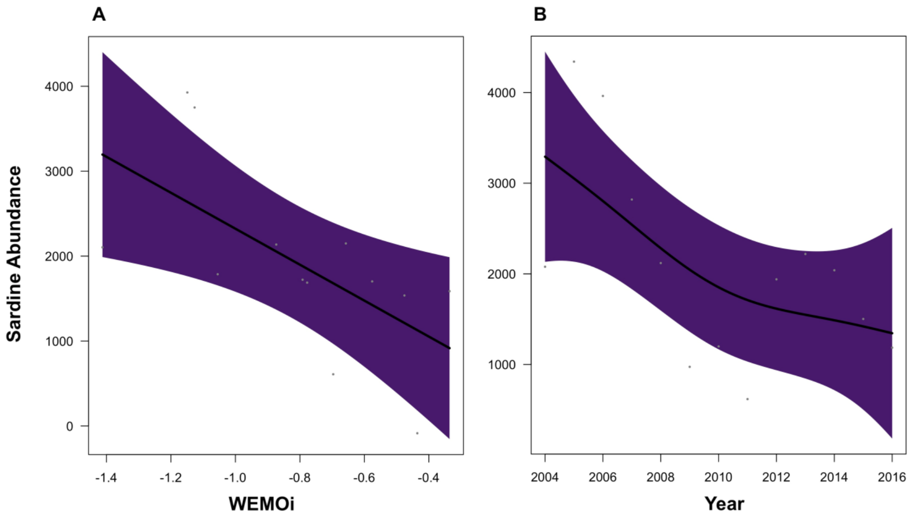

Figure 6: Partial GAM plots of sardine (*Sardina pilchardus*) abundance (in number of individuals). Significant partial effects of the (A) Western Mediterranean Oscillation index (WEMOi) and the (B) year effect are shown. The shaded areas indicate the 95% confidence interval.

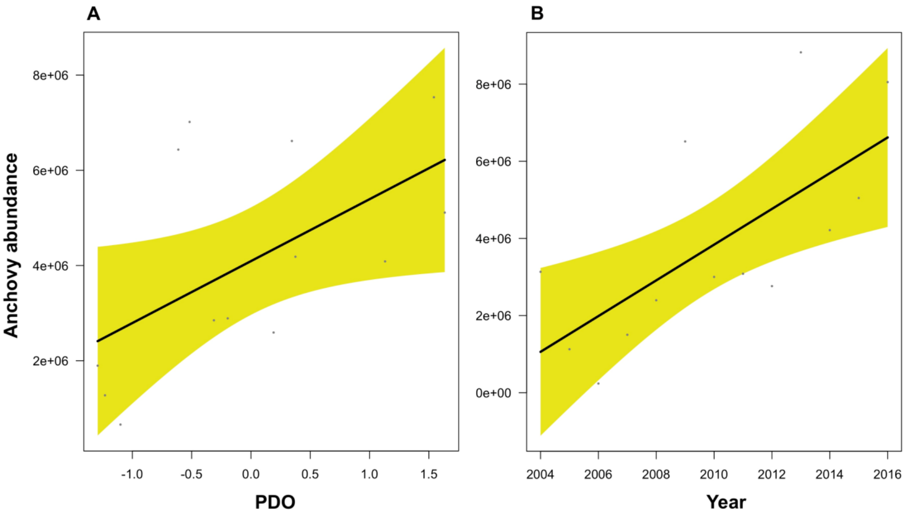

Figure 7: Partial GAM plots of anchovy (*Engraulis encrasicolus*) abundance (in number of individuals). Significant partial effects of the (A) Pacific Decadal Oscillation (PDO) and the (B) year variable are shown. The shaded areas indicate the 95% confidence interval.

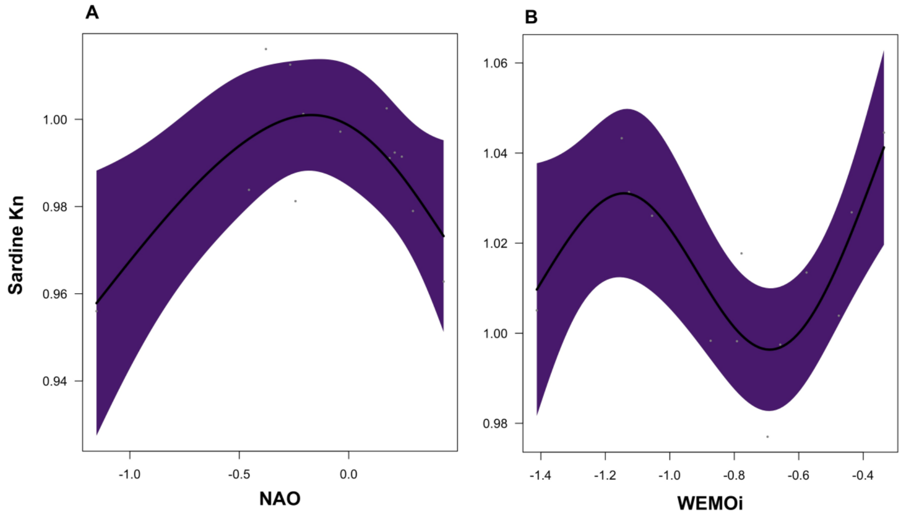

Figure 8: Partial GAM plots of sardine (*Sardina pilchardus*) Kn. Significant partial effects of the (A) North Atlantic Oscillation (NAO) and (B) Western Mediterranean Oscillation index (WEMOi). The shaded areas indicate the 95% confidence interval.

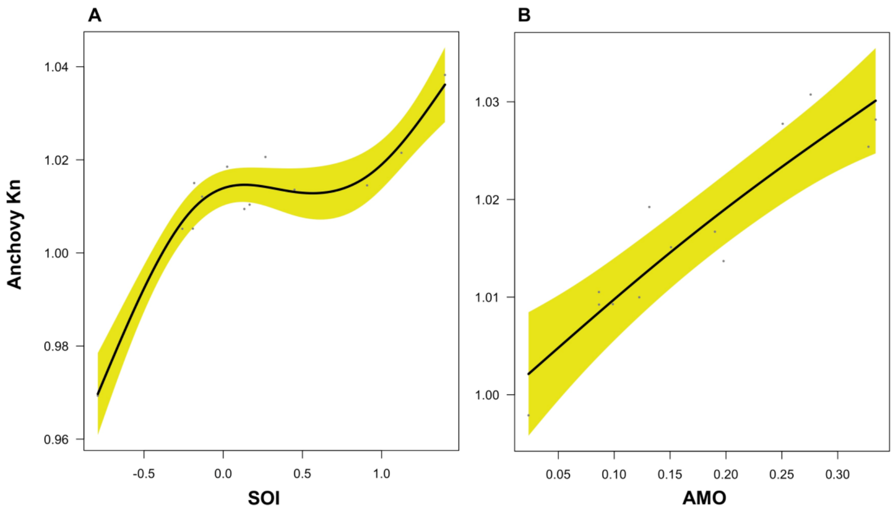

Figure 9: Partial GAM plots of anchovy (*Engraulis encrasicolus*) Kn. Significant partial effects of the (A) Southern Oscillation Index (SOI) and (B) Atlantic Multidecadal Oscillation (AMO) indices are shown. The shaded areas indicate the 95% confidence interval.

AUTHOR STATEMENT

Author Contributions

Conception and methodology design: JCB; data collection: JCB, MGP, AG, CGS; data analysis: MGP, IAC, CGS; first draft: JCB and MGP. All authors critically reviewed the drafts and gave final approval for publication.

Ethical Statement

No specific authorization was required for any of the activities undertaken during this study, which was conducted using statistical fishery data available online.

Conflicts of interest/Competing interests

Dear Editor,

In relation to the accompanying paper entitled "**Long-distance effect of PDO and SOI on European sardine and anchovy in the Western Mediterranean Sea**"
Authors' declarations of interest: the authors declare no conflict of interest

Thank you for your consideration, and we look forward to hear from you.

Sincerely,

Dr. José Carlos Báez
At the head of all authors