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INFLUENCE OF OCEANO-METEOROLOGICAL CONDITIONS ON THE BEHAVIOUR, DISTRIBUTION AND ABUNDANCE OF THE NORTHEAST ATLANTIC ALBACORE

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SUMMARY

Oceano-climatic variability influences marine fish stocks. In this regard, it is logical to think that fluctuations in environmental conditions would affect the optimum habitat of species, with probable consequences on their behaviour, distribution and abundance. The objective of this study was to characterise the oceanographic conditions in the distribution area of albacore within the Northeast Atlantic Ocean; further, environmental reasons for interannual fluctuations in stock abundance were investigated. In particular, this work focused on those years when catches for the Basque fleet were very low (e.g. 2000, 2001 and 2009, 2010) in comparison to other years with favourable fishing seasons (2005, 2006). This study presents some preliminary results on the potential importance of the Gulf Stream index for albacore survival and recruitment; it also highlights the relevance of parameters such as sea surface temperature, mesoscale structures and stratification of the water column for the catchability of albacore, by local fishing fleets.

RÉSUMÉ

La variabilité océano-climatique influence les stocks de poissons marins. À cet égard, il est logique de penser que les fluctuations dans les conditions environnementales affecteraient l'habitat optimum des espèces, avec des conséquences probables sur leur comportement, distribution et abondance. L'objectif de cette étude était de décrire les conditions océanographiques de la zone de distribution du germon dans l'océan Atlantique Nord-Est et de déterminer les conditions environnementales qui entraînent des fluctuations interannuelles dans l'abondance du stock. Les travaux se sont notamment concentrés sur les années au cours desquelles les prises de la flottille basque étaient très faibles (2000, 2001, 2009 et 2010) par rapport à d'autres années aux saisons de pêche plus favorables (2005 et 2006). Cette étude présente quelques résultats préliminaires concernant l'importance potentielle de l'indice du Gulf Stream pour la survie et le recrutement du germon et met en lumière l'importance des paramètres tels que la température de surface de la mer, les structures de méso-échelle et la stratification de la colonne d'eau pour la capturabilité du germon par les flottilles de pêche locales.

RESUMEN

La variabilidad oceano-climática influye en los stocks de peces marinos. En este sentido, es lógico pensar que las fluctuaciones en las condiciones medioambientales afectarían al hábitat óptimo de las especies, con consecuencias probables en su comportamiento, distribución y abundancia. El objetivo de este estudio era describir las condiciones oceanográficas en la zona de distribución del atún blanco dentro del Atlántico nororiental, además, se investigaron las razones medioambientales de las fluctuaciones interanuales en la abundancia del stock. En particular, este trabajo se centró en los años en los que las capturas de la flota vasca fueron muy bajas (a saber, 2000, 2001 y 2009, 2010) en comparación con otros años con temporadas de pesca más favorables (a saber, 2005, 2006). En el estudio se presentan algunos resultados preliminares de la importancia potencial del índice de la Corriente del Golfo para la supervivencia y reclutamiento del atún blanco, y se resalta la importancia de parámetros como la temperatura de la superficie del mar, las estructuras meso-escala y la estratificación de la columna de agua en la capturabilidad del atún blanco por parte de las flotas pesqueras locales.

KEYWORDS

Albacore, Thunnus alalunga, fisheries oceanography, abundance, recruitment, catchability, environmental conditions, habitat, Northeastern Atlantic, Bay of Biscay

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1 Introduction

Albacore (*Thunnus alalunga*) is a highly migratory pelagic species with a high level of metabolic activity. One characteristic is its thermoregulatory capacity allowing them to keep an internal warmer temperature in comparison to the environmental water temperature. This characteristic allows them to swim through water masses in a wide range of temperatures, both horizontally and vertically. And within its wide distribution albacore shows some clear preferential ranges for several oceanographic parameters. Dufour (2010) observed that worldwide albacore preferred waters with temperature ranges of 14-22ºC at sea surface, and of 12-20ºC at 100 m depth. In addition to water temperature, other hydrographic parameters that characterise albacore habitat are as follow: salinity values between 35 and 38 PSU, chlorophyll concentration lower to 10 mg/m^2 and a neutral sea level anomaly.

In the North Atlantic Ocean, albacore latitudinal migrations follow the isotherms between 16 and 21ºC (Havard-Duclos, 1973). Further, thermal preferences are different according to the age: albacores of age 1 and age 4 prefer warmer waters (20-21ºC), 2-year individuals waters ranging between 18 and 19ºC and albacores of age 3 waters of 16 to 17ºC (Sagarminaga and Arrizabalaga, 2010).

Zainuddin *et al.* (2004) observed that albacore CPUE (catches per unit of effort) distribution was not only related to water temperature, but also to chlorophyll concentration at sea surface, with preferences for concentrations around 0.3 mg/m^3. This conclusion agrees well with the result of a study carried out with landings of the Basque fleet (baitboat and trolling line), where catches were made in waters with chlorophyll concentration of 0.2-0.4 mg/m^3.

Further, albacore distribution areas in the northwestern Pacific Ocean were found to occur in waters with high Eddy Kinetic Energy (EKE) and strong geostrophic currents, showing that tuna aggregations were related to anticyclonic gyres (Zainuddin *et al.*, 2006).

Albacore shows a large geographic distribution covering the whole North Atlantic up to 55ºN. It is a highly migratory species which, depending on the season of the year, varies its distribution area. Both adults and juveniles spend winter time in central tropical waters of the North Atlantic Ocean. In spring, with the warming of the waters, adults initiate a reproductive migration to the Sargasso Sea where spawning occur between April and September (Santiago, 2004). In spite of the limited knowledge about early stages of albacore, it has been seen that in summer, immature individuals carry out a trophic migration to northern latitudes, leading to productive areas of the Bay of Biscay and the southeast of Ireland (Arrizabalaga *et al.*, 2002).

In their trophic migration to northern latitudes, albacores are fished with surface fishing gears such as baitboat and trolling line, and more recently also with pelagic trawling. Fishing season takes place between June and October. It begins close to Azores Islands (25-30ºW) and moves northeastwards during the following weeks and months, up to the Bay of Biscay and the south of Ireland (40-50ºN). Fishing fleet catches juveniles of 1-4 ages, but mainly individuals of 2-3 years. However, the latter group of tunas (ages 2-3) has diminished in the Bay of Biscay in recent years; by contrast, they have been fished in Ireland. Consequently, Basque fishing fleet required to go over longer distances to look for the fish that did not enter into the Bay of Biscay.

Considering, on the one hand, that albacore shows environmental preferences to optimize its physiologic functions and to conduct seasonal migrations and, on the other hand, accounting for the low catch records recently registered by the Basque fleet, with scarce presence of albacore in the Bay of Biscay, this study aims to understand the oceanographic conditions which determine the presence and availability of this species for local main fisheries (bait boat, troll and pelagic trawl).

2 Objectives

The main objective of this work was to characterize the environmental conditions that occur in the distribution area of albacore and to study the influence of oceano-meteorological parameters on the behaviour and interannual abundance variability of this species. To this end, two spatio-temporal approaches were considered:

- Climatic conditions at a large scale (North Atlantic) through the study of low-frequency teleconnection patterns.

- Local conditions at a regional scale (Bay of Biscay) through the study of oceano-meteorological conditions at the main albacore fishing areas.

3 Material and methods

3.1 Study area

Generally speaking, the study area of the present work covers the North Atlantic Ocean in a global context. However, the study focuses more deeply in the area located between Azores, Bay of Biscay and Ireland, that is to say, the main fishing area of the Basque fleet targeting albacore.

3.1.1 North Atlantic

In the North Atlantic, warm and cold currents surround the North Atlantic oceanic gyre, which flows clockwise all along the anticyclone of Azores. The main currents are the Gulf Stream in the west, the North Atlantic Current in the north, the Canary Current in the east and the North Equatorial Current in the south, closing the circular system.

The northwestern Atlantic is mainly dominated by the Gulf Stream, which moves a warm saline water mass coming from the Gulf of Mexico to the north. The limit between the warm waters of the current and the cold waters located at the north is known as the North Wall. The Gulf Stream flows along the southeast coast of United States to finally separate from the continent towards oceanic waters; at this stage it is known as the North Atlantic Current and it flows towards Europe.

A great part of the atmospheric circulation is related to teleconnection indices, such as the North Atlantic Oscillation (NAO) and the Eastern Atlantic Pattern (EA) (Gonzalez *et al.*, 2011). The influence of both indices is more intense in autumn and winter. Positive episodes of NAO are related to cold and dry winters, while positive phases of EA are associated with dry and warmer climate. It should be noted that NAO is an important descriptor of the atmospheric variability at global scale (Northern Hemisphere), whereas EA exerts an important influence on a regional scale in the Bay of Biscay (Valencia *et al.*, 2009). In addition, global indices like the Atlantic Multidecadal Oscillation (AMO) and the Gulf Stream index (GSI) are also influential at the North Atlantic scale: AMO index represents water temperature conditions in the North Atlantic Ocean, whereas GSI represents the position of the north wall which, in turn, indicates the intensity and latitudinal location of the North Atlantic Current. Several authors (Taylor and Stephens, 1998; Curry and McCartney, 2001) concluded that the latitude of the north wall of the Gulf Stream corresponds to the atmospheric variability of the North Atlantic, and therefore, to the NAO index that represents more than the 36% of the variance of the surface atmospheric pressure between December and March (Hurrel, 1995).

3.1.2 Bay of Biscay

The Bay of Biscay is located in the northeastern Atlantic Ocean; it extends along the western French and northern Spanish coasts, from the peninsula of Brittany in France up to the Ortegal cape in Galicia (Spain) (**Figure 1**). The Bay reaches more than 4000 m depth in the abyssal plain. The continental slope is the transition between the abyssal plain and the continental shelf; it is characterised by a sharp slope and it is fractured by several canyons. In the northern area, the width of the Armorican shelf goes from 150 to 180 km and the length is about 300 km. In the southern area, the width of the Armorican shelf extends between 150 and 50 km and is has a length of about 250 km. The Spanish shelf shows an east-west orientation and it is narrow, with an average width between 30 and 40 km (Koutsikopoulos and Le Cann, 1996).

The atmospheric circulation depends on two activity centres: an anticyclonic area located south to the 40ºN parallel, centred close to Azores, and a low pressure area centred on the line of latitude 60ºN, close to Iceland. Between both areas, the predominant winds blow from the west-southwest, with stronger intensity in winter but weaker and more irregular in summer. Consequently, the area is characterized by a noticeable seasonality: in spring and summer, winds mainly blow from the north, whereas in autumn and winter southwesterly winds are more frequent (OSPAR, 2000).

The surface water circulation of the Bay of Biscay is mainly driven by wind forcing and constrained by the complex and irregular submarine topography and orientation of the coast. In addition, continental water inputs modify sea water characteristics and they establish a marked spatial variability. The rivers with more volume that flow into the Bay of Biscay are the Loire, Adour, Dordogne and Garonne rivers, all of them belonging to French basins.

The main characteristics of the water circulation of the Bay of Biscay are summarised in **Figure 1**. The Bay is situated in the intergyre area, between the current of Azores (belonging to the subtropical anticyclonic gyre) and the North Atlantic current (belonging to the subpolar cyclonic gyre). In this regard, the central area of the Bay is characterised by a weak anticyclonic circulation (~1-2 cm/s) (Koutsikopoulos and Le Cann, 1996). However, the surface circulation over the abyssal basin is namely seasonal, in response to the Ekman transport induced by the winds. The main characteristic of this oceanic zone is the presence of mesoscale eddies. They are generated due to abrupt changes in the bathymetry of the area such as canyons, which interrupt the winter slope current (*Navidad* flow). The winter slope current enters the Bay of Biscay in the area of Cape Finisterre. The warm water flows eastwards over the Cantabrian continental slope. Pingree and Le Cann (1990) showed that despite the relatively weak intensity of the slope current (5-10 cms^{-1}), it has a marked seasonality with warm water flowing along the Portuguese and Spanish slopes in winter. Part of this flow continues towards the Pole, following the French continental slope; but given the abrupt changes in the topography of the area such as Cape Ortegal, Estaca de Bares and the canyon of Cape Ferret, the slope current is partly interrupted forming the abovementioned oceanic eddies (Garcia-Soto *et al.*, 2002). Pingree and Le Cann (1992) named these oceanographic structures “SWODDIES” (Slope Water Oceanic eDDIES), which are oceanic eddies that retain water coming from the continental slope, where these structures are generated. Eddies participate in the interchange of heat, salt, contaminants, nutrients, plankton, etc., between the continental slope and the abyssal plain.

3.2 Data sources

3.2.1 North Atlantic albacore population trends

Time-series (1930-2007) with annual values of abundance (number of individuals) at age, recruitment (number of individuals at age 1), total and adult biomass (tonnes) for the whole stock of the North Atlantic were obtained from the last stock assessment carried out by ICCAT (ICCAT, 2009).

3.2.2 Catches and CPUE

Annual landings of albacore were analysed in order to determine favourable and unfavourable years of fishing seasons. The study was based on data from the Basque fleet, Spanish fleet, and the whole stock of the North Atlantic.

Basque fleet landings for trolling line (1995-2011) and baitboat (1996-2011) were used to estimate albacore abundance indices based on CPUE. The CPUE index was built both for total catches and for catches classified by commercial category (small, medium and large albacore). The effort was estimated accounting for the time passed between consecutive landings. After the filtering of the database (elimination of non-reasonable data), the nominal CPUE were aggregated in order to obtain monthly abundance indices.

Logbooks of trollers and baitboats from the fishing sector of Bizkaia and Gipuzkoa (Spanish Basque Country), and of pelagic trawlers from the sector of Bayonne (French Basque Country) were used (**Table 1**). From these logbooks, date and position of the catches were obtained.

3.2.3 Environmental data

3.2.3.1 Global climatic indices

Accounting for their area of influence, several climatic indices were selected (**Table 2**). Much of the variability of the North Atlantic atmospheric circulation is explained by teleconnection indices such as the North Atlantic Oscillation (NAO) and the Eastern Atlantic pattern (EA). The North Atlantic multidecadal oscillation (AMO) represents the sea surface temperature (SST) oscillation of the North Atlantic Ocean. Lastly, the Gulf Stream index (GSI) measures the position of the north wall of the Gulf Stream.

3.2.3.2 Oceanographic parameters

With the aim of building SST and SST anomaly maps for the study period, AQUA MODIS 4km data (oceancolor.gsfc.nasa.gov) were used.

In addition, environmental information at the position and date of albacore catches was obtained. The oceanographic parameters selected are summarised in **Table 3** and the methodology used for data extraction is explained in the following lines.

The high resolution 3D prognostic ocean model ROMS (Regional Ocean Model System, Shchepetkin and McWilliams 2005), forced by detailed atmospheric, hydrologic and oceanic information was used. The model domain covers all the Bay of Biscay, extending from the Spanish coast (40.5ºN) to the south of United Kingdom (about 52.5ºN) and from the French coast to the longitude 13ºW. The current configuration for the Bay of Biscay is an extension of a configuration limited to the southern part of the Bay (Ferrer *et al.*, 2009) and the bathymetry was obtained through interpolation, following an optimization analysis. ROMS for the Bay of Biscay computes the primitive equations on a 6.6 km grid in the horizontal and on 32 no-equally distributed σ-levels in the vertical.

This model uses mass conservation equations to simulate the variability of oceanic processes, including high-frequency (tides, daily thermal cycles and precipitation), low frequency (atmospheric perturbations, mesoscale variability) and seasonal scales (river runoffs, winter convection and summer stratification). The atmospheric information has been taken from the NCEP re-analyses database (http://www.ncep.noaa.gov/): wind stress, heat fluxes, net short wave radiation, and precipitation. The initial and bounday conditions for currents, temperature, salinity and nitrate are interpolated on the grid from the World Ocean Atlas 2005 (WOA05) developed by the National Oceanographic Data Center (NODC) of the NOAA. The water level is specified for initial condition but also at each time step along the open boundaries, using the OSU TOPEX/Poseidon Global Inverse Solution version 5.0 (TPXO.5, global model of ocean tides). River runoff data are prescribed as boundary conditions on momentum, salinity, temperature and nitrate. Daily flow data are used from observations in the about 20 most important rivers on the French and Spanish coasts. The temperature and nitrate concentrations of these rivers are prescribed from observations, when available, using monthly means. After a 1-year of rotation (year 1997) to reach equilibrium, the simulation covers the period 1998-2009, with a time step of 15 min.

Sea level anomaly (SLA) data come from altimetry radars located on board several satellites. From the interpolated SLA maps, zonal (*Ug*) and meridional (*Vg*) geostrophic current (GC) are estimated following these equations:

$$Ug = -\frac{g}{f} \cdot \frac{\Delta SLA}{\Delta y}$$

$$Vg = \frac{g}{f} \cdot \frac{\Delta SLA}{\Delta x}$$

Lastly, with the aim of obtaining the energy associated with mesoscale processes of the area, the Eddy Kinetic Energy (EKE) was estimated:

$$EKE = \frac{1}{2} \cdot (Ug^2 + Vg^2)$$

3.3 Data analysis

3.3.1 Large scale (North Atlantic)

In order to explore if the different global indices exert any influence on albacore, correlation values were calculated between the global climatic indices and each of the following biological series: recruitment, abundance at age 2 and 3 and catches by the fleet.

3.3.2 Regional-local scale (from Azores to the Bay of Biscay)

Firstly, environmental preference ranges for which albacore landings are more frequent were defined. By using histograms, minimum and maximum values were identified, between which at least 90% of the catches were made. Such ranges were estimated for each of the oceanographic parameter considered in this study and separately for each fishing gear. In addition, ranges in which at least 50%, 80% and 100% of the catches were made were also identified. Further, with the aim of analysing whether the oceanographic conditions in the set positions were different in the Bay of Biscay and out of the Bay, different histograms were built separating captures carried out in the Bay of Biscay (42-48ºN and 0-8ºW), out of the Bay of Biscay (all the catches recorded west of 8ºW) and in Ireland (north of 48ºN and 20-0ºW) (**Figure 2**).

Secondly, with the aim of understanding the shared variability of the environmental parameters used for the present study, a Principal Component Analysis (PCA) was applied to the variables extracted from ROMS. Based on the PCA results, the principal components were used as explanatory parameters for daily catches; Generalized Additive Models (GAMs) were used in order to model the variations in daily catches.

At the same time, environmental influence on interannual landings variability was studied. The objective was to determine oceanographic conditions for anomalous years in terms of albacore catches. In this regard, different percentiles (P80, P20 and P90, P10) of catches series were calculated and then graphically represented. Such plots allowed us to identify years with catch records higher than P80 or even P90, which were defined as favourable (“good”) years of catches, and years with catch records lower than P20 or even P10, which were described as unfavourable (“bad”) years of catches.

Once extreme years were identified, several oceanographic parameters were studied in order to understand the differences in catches between favourable and unfavourable years. Accounting for the importance of the SST in the distribution and migration of albacore tunas, maps of SST distribution were drawn for the months of higher fishing activity (June, July, August and September) for the years of interest. Albacore catches were represented on the maps. Further, altimetry, geostrophic currents and EKE information was also considered at the position of the catches. This information made it possible to check whether the differences between years with high and low catches could be explained by means of interannual variations in eddy abundance or EKE values of the area.

4 Results and Discussion

Two mechanisms could be the reason of the variability/decrease in albacore catches observed recently in the Bay of Biscay. Firstly, global oceano-meteorological conditions can influence recruitment levels of the stock, which, in turn, affects the stock biomass. Secondly, regional-local environmental conditions in the fishing area could directly affect albacore catchability, and thus, influence the fishing success of the surface fleet in the Northeast Atlantic. Both hypotheses have been previously analysed by several authors without reaching a definitive conclusion (Ortiz de Zárate *et al.*, 1998; Santiago, 1998, 2004; Bard and Santiago, 1999; Bard, 2001).

4.1 Large scale (North Atlantic)

Among the selected global indices (NAO, EA, AMO and GSI), GSI index was the climatic index that showed a highly significant ($p<0.01$) negative correlation with albacore population trends (**Figure 3**), i.e. years with positive GSI index were found to be unfavourable for albacore. Positive values of this index are indicative of a northern displacement of the Gulf Stream, whereas in years with negative GSI index, the stream is located at southern positions probably favouring the recruitment and survival of albacore. Abundance indices also showed a negative correlation with GSI, but with an increasing time-lag according to the age category. Additionally, total catches and CPUE series showed an inverse correlation with GSI, which indicates that a southward displacement of the Gulf Stream position seems to favour albacore catchability; a northward displacement of the Gulf Stream and a higher transport associated with this current could indicate a northward distribution and migration of albacore, out of area covered by Basque fishing fleet (Sherman and Skjoldal, 2002), and therefore negatively affecting its catchability. In this regard, several studies have concluded that the variability in the Gulf Stream, and in particular that associated with the position of the North Wall, can influence tuna distribution and therefore, their catchability (Lavín *et al.*, 2007).

Given the high correlation between recruitment and annual GSI index, we also explored the relation with quarterly means of the global index, in order to study if the correlation was higher for a particular season of the year. **Figure 4** shows the correlation coefficient between albacore recruitment and quarterly means of GSI. The correlation between both variables was higher for the first semester of the year, particularly between January and May. When analysing this result, it is relevant to consider that when sea water warming starts, adults migrate to Sargasso Sea for their reproduction; afterwards, from April to June, juveniles and pre-adults (ages 1 to 4) initiate a trophic migration to Northeast Atlantic (Santiago, 2004) searching for productive waters.

4.2 Regional-local scale (from Azores to the Bay of Biscay)

Accounting for albacore distribution and in particular to its annual displacement to the Bay of Biscay, this section explores albacore oceanographic preferences during the months of fishing season (June to November), from Azores area to the inner Bay of Biscay and also to Irish waters.

The extraction of oceanographic information at the position and date of each catch permits building tables with optimum minimum and maximums values for tuna presence. **Table 4, Table** 5 and **Table 6** summarise preference ranges for each of the studied variable, between which 100%, 90%, 80% or 50% of catches were recorded. Following this procedure, oceanographic conditions at catches made by different fishing gears were characterised.

Similarly, preference ranges at different fishing areas (**Figure 2**) were also compared and the results can be found in **Table 7**. There are differences in thermal preferences, regarding plankton concentration and also in terms of energy and altimetry values. In the Bay of Biscay, catches are made in warmer and more stratified waters as it was expected. However, catches within the Bay occurred in waters with less concentration of chlorophyll and zooplankton than in waters out of the Bay. Lastly, albacore catches out of the Bay of Biscay occurred in waters with stronger geostrophic currents and consequently higher EKE.

Figure 5 shows the results of the PCA analysis carried out with the main 10 oceanographic parameters extracted from the ROMS model. The analysis highlights the correlation between biotic variables (chlorophyll a and zooplankton concentration at surface and subsurface depths), which in turn are oppositely situated in the graph to the thermal variables. Therefore, this first component represents biotic and thermal aspects of the parameters. The second component of the PCA is correlated with the depth of the isotherm of 15ºC in the positive semi-axis and the temperature gradient between surface and 30m depth in the negative semi-axis. This second component therefore represents the level of mixing/stratification of the water column (highly stratified in the negative semi-axis and high mixing in the positive semi-axis). The first two components of the PCA represent the 81% of the variability of data analysed.

The first two components of the PCA were used to model daily catches of albacore made by baitboat, trolling line and pelagic trawling fleets. Different GAMs were built for different fishing gears. The trophic/thermal component (Dim. 1) showed a significant effect only in those catches fished by baitboat (**Figure 6**) and trolling line gears (**Figure 7**). Regarding the mixing component (Dim. 2), it seems to have a significant effect on catches for all fleets: albacore catches made by pelagic trawlers were found to be higher with an optimum mixing of the water column (**Figure 8**), whereas catches made by baitboat (**Figure 6**) and trolling line (**Figure 7**) fleets decreased with the mixing of the water column. That is, lower catches made by pelagic trawlers and higher catches by baitboat and trolling line are related with higher temperature gradients (between surface and 30m depth). Baitboat and trolling line are surface gears; therefore, the significant negative effect of the water column mixing on albacore catches made by these gears can be easily understood: with a mixing of the upper water column the catchability of the fish decreases, since tuna fishes can find easier to scape to deeper levels in the water column. However, in the case of pelagic trawling this variable has the inverse effect, where tuna catchability is higher for optimum values of mixing. This can be explained with a vertical distribution of albacore at deeper levels where the manoeuvre of the net can be easier. The fact that the trophic/thermal component seems to have no effect on pelagic trawling catches, while it significantly affects catches made by surface gears (baitboat and trolling line) is consistent with the passive nature of these gears (based on the feeding behaviour of tunas).

Further, given the high interannual variability in albacore catches, favourable and unfavourable years were identified in order to determine environmental parameters responsible for such extreme situations. Figure 9 shows the interannual variability in albacore catches from 1950 to 2011. From mid-1970s to the beginning of 90s, albacore catches showed the highest records with peaks in some years like 1979, 1983 and 1987. However, from then onward, annual catches decreased until 2001 and 2002, when very low catches were registered (similar to the low value of 1955). In the period 1987-2000 the fleet reduced significantly from 318 vessels in 1987 to 181 vessels in 2000 (Santiago, 2004). Afterwards, the Basque fleet fished again in average levels, but the last three years of the time-series (2009, 2010 and 2011) went back again to very low catches. A similar trend is observed in CPUE values per fishing gear. Baitboat fleet suffered the worst years in 2001 and 2002 with catches below the 10% percentile (**Figure 10**), similar to the trolling line fleet (**Figure 11**). By contrast, 2006 for baitboat fleet (**Figure 10**) and 2005-2006 for trolling line fleet (**Figure 11**) were the best years in terms of albacore catches.

Can oceanography explain such extreme events in albacore fishing seasons?

SST maps show that a high part of the catches occur in the yellow-green band of the temperature scale (**Figure 12**); further, albacore catches move following this band as the season progresses. However, once in the Bay of Biscay, catches are registered in higher temperatures. Despite sea temperature is a factor that somehow limits and guides albacores on their migration eastwards, it is not determinant to explain the reason of unfavourable fishing seasons such as 2010 and 2011 for instance.

Regarding the marine dynamics in the Bay of Biscay, eddy abundance was not significantly different between satisfactory and unsatisfactory fishing seasons, so as to explain the extreme differences in albacore catches. However, when visualizing the interannual variability of eddies in the study area during summer time, years such as 2002, 2010 and 2011 ("bad" years in terms of albacore catches in the Bay of Biscay) showed an area of high EKE associated with energetic eddies in the area limited by 8ºW-12ºW and 43ºN-47ºN (**Figure 13**). This group of energetic structures was not visible in 2005 and 2006 ("good" years in terms of albacore catches in the Bay of Biscay) (**Figure 13**). A priori, a group of oceanic mesoscale structures like this is not a physical barrier for tunas in their route to the inner Bay of Biscay. By contrast, they could delay their entry to the Bay if they have remained associated with those structures for a while. It seems that these intense mesoscale structures located to the northwest of Galicia, in years when albacore catches in the Bay of Biscay were extremely low, could have modified either directly or indirectly the usual migration of albacore, hypothesis that should be verified with further research.

Lastly, there is an additional oceanic process that varies interannually. The North Atlantic current exhibits an intense signal of EKE.

Figure 14 shows average EKE distribution for the period 1992-2011 from the Bay of Biscay to the west. It can be seen that EKE is significantly higher out of the Bay of Biscay, mainly between 25ºW and 40ºW; in fact, EKE distribution in this area represents the track of the North Atlantic Current: there is a high energetic corridor given the North Atlantic current, and most of the catches registered in the oceanic area (west of 11ºW) were made in the limit of such corridor. In order to verify whether there have been interannual variations in the eastern extension of the North Atlantic current, that is to say, if the North Atlantic current has reached waters more or less closer to the Bay of Biscay during the study period, the following analysis was carried out: the annual average value of EKE for the month of July was calculated focusing on the area between 42ºN and 46ºN (being July and 42-46ºN area the month and the band through which albacore goes into the Bay of Biscay).

Figure 15 shows a clear interannual variability in the eastward extension of the North Atlantic current (red pixels); closer to the Bay of Biscay, EKE intensity diminishes significantly. It should be noted that isolated pixels with high EKE values probably correspond to mesoscale eddies. Regarding the interannual variability in the extension of the North Atlantic current, in 2000 the area with maximum EKE is located west to the 35ºW. From 2001 to 2004 the highest values of EKE reached eastern longitudes, up to 28ºW. In 2005, the extension to the east is reduced and in 2006 it reached again the minimum extension. From 2007 onwards, the extension of the North Atlantic current expanded again eastwards. In summary, in 2005 and mainly in 2006 (years with good albacore catch records in the Bay of Biscay) the extension of the more energetic signal of the North Atlantic current was located in more westerly waters, in comparison with the rest of the years when the North Atlantic current reached eastern waters. Therefore, the longitudinal extension of the North Atlantic Current seems to be related to the albacore catches registered in the Bay of Biscay.

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Table 1. Catch time-series used in the present study.

Fishing gear	Period	Number of Observations
Trolling line	1985-2005	14574
Pelagic trawl	2002-2011	830
Baitboat	1985-2005	10365
Baitboat	2005-2011	8813

Table 2. Summary of the global climatic indices utilized, including the available time period and the corresponding acronym.

Global climatic indices	Study period	Acronym	Data source
North Atlantic Oscillation	1950-2012	NAO	http://www.cpc.noaa.gov
Eastern Atlantic pattern	1950-2012	EA	http://www.cpc.noaa.gov
North Atlantic multidecadal oscillation	1950-2012	AMO	http://www.esrl.noaa.gov
Gulf Stream index	1966-2012	GSI	http://www.pml-gulfstream.org.uk

Table 3. Summary of the oceanographic parameters utilized, including unit, study period and acronym.

Oceanographic parameters	**Unit**	**Study period**	**Acronym**
Temperature at 2m depth	ºC	1998-2009	T2
Temperature at 30m depth	ºC	1998-2009	T30
Salinity at 2m depth	g/kg	1998-2009	S2
Salinity at 30m depth	g/kg	1998-2009	S30
Chlorophyll a concentration at 2m depth	mgChla/m^3	1998-2009	CH2
Chlorophyll a concentration at 30m depth	mgChla/m^3	1998-2009	CH30
Zooplankton concentration at 2m depth	mgC/m^3	1998-2009	ZOO2
Zooplankton concentration at 30m depth	mgC/m^3	1998-2009	ZOO30
Depth of 15ºC isotherm	m	1998-2009	Z15
Temperature gradient between 2m and 30m	ºC	1998-2009	G
Sea level anomaly	cm	1992-2012	SLA
Geostrophic current velocity	cm/s	1992-2012	GCA
Eddy Kinetic Energy	cm^2/s^2	1992-2012	EKE

Table 4. Preference ranges for each of the oceanographic parameters between which 100%, more than 90%, more than 80% and more than 50% of the catches by baiboat were made.

	Baitboat							
	100% of sets		**>90% of sets**		**>80% of sets**		**>50% of sets**	
	Min.	**Max.**	**Min.**	**Max.**	**Min.**	**Max.**	**Min.**	**Max.**
T2	15	23	16	21	17	20	18	19
T30	13	19	15	18	16	18	16	17
Z15	12	96	20	70	27	55	27	52
G	0	7	0	5	0	4	0	2
S2	35	35.9	35.6	35.8	35.6	35.8	35.7	35.8
S30	35.1	35.8	35.6	35.8	35.7	35.8	35.7	35.7
CH2	0.1	2.8	0.2	0.6	0.2	0.4	0.2	0.3
CH30	0.2	1.5	0.2	0.8	0.3	0.6	0.3	0.5
ZOO2	0	8.6	0	2	0.2	1.3	0.3	0.8
ZOO30	0	8	0	3	0.5	2.6	0.8	1.7
SLA	-9	19	-1	8	0	7	2	5
EKE	0	277	0	30	0	15	1	8
GCA	0	24	1	8	1	6	2	4

Table 5. Preference ranges for each of the oceanographic parameters between which 100%, more than 90%, more than 80% and more than 50% of the catches by trolling line were made.

	Trolling line							
	100% of sets		**>90% of sets**		**>80% of sets**		**>50% of sets**	
	Min.	**Max.**	**Min.**	**Max.**	**Min.**	**Max.**	**Min.**	**Max.**
T2	15	23	16	21	17	20	17	18
T30	13	19	14	17	15	17	15	16
Z15	9	87	20	50	24	45	25	37
G	0	5.9	0	4	1	4	2.4	3.5
S2	35	35.9	35.6	35.8	35.6	35.8	35.6	35.7
S30	35.3	35.9	35.5	35.7	35.6	35.7	35.6	35.6
CH2	0.1	1.3	0.2	0.5	0.2	0.4	0.3	0.4
CH30	0.2	1.2	0.3	0.7	0.3	0.6	0.4	0.6
ZOO2	0	4.7	0	2.5	0.2	1.9	0.2	1.2
ZOO30	0	5.7	0	2.5	0.2	1.9	0.2	1.2
SLA	-12	19	-4	10	0	8	1	5
EKE	0	343	0	80	0	48	0	14
GCA	0	26	1	12	1	10	2	6

Table 6. Preference ranges for each of the oceanographic parameters between which 100%, more than 90%, more than 80% and more than 50% of the catches by pelagic trawling line were made.

	Pelagic trawling							
	100% of sets		**>90% of sets**		**>80% of sets**		**>50% of sets**	
	Min.	**Max.**	**Min.**	**Max.**	**Min.**	**Max.**	**Min.**	**Max.**
T2	15	23	16	21	16	20	18	20
T30	14	19	15	18	16	18	16	17
Z15	19	90	30	60	35	58	40	50
G	0	6.8	0	4	0	3	0	2
S2	35	35.9	35.5	35.8	35.6	35.8	35.6	35.7
S30	35.3	35.8	35.5	35.8	35.6	35.7	35.6	35.7
CH2	0.1	1	0.2	0.5	0.2	0.4	0.2	0.3
CH30	0.1	1.1	0.2	0.7	0.3	0.6	0.3	0.4
ZOO2	0	4	0	1.5	0.2	1.2	0.2	0.7
ZOO30	0	4	0	2.5	0.3	1.9	0.8	1.6
SLA	-5	18	1	10	2	9	3	7
EKE	0	518	0	25	0	14	0	5
GCA	0	32	1	6	1	5	2	4

Table 7. Summary of the preference ranges for each of the oceanographic parameters in three different areas considered: west of 8ºW, in the Bay of Biscay and in Ireland.

	West of 8ºW	**Bay of Biscay**	**Ireland**
T2	17-19	19-20	16-19
T30	14-16	16-17	14-16
Z15	20-40	40-50	20-40
G	2-3	3-4	2-3
S2	35.6-35.7	35.7-35.8	35.5-35.6
S30	35.6-35.7	35.6-35.7	35.5-35.6
CH2	0.3-0.4	0.2-0.3	0.3-0.4
CH30	0.5-0.7	0.3-0.4	0.5-0.7
ZOO2	1-2	1-2	1-2
ZOO30	2-3	2-3	2-3
SLA	0-10	0-10	0-10
EKE	0-60	0-20	0-20
GCA	0-12	0-6	0-6

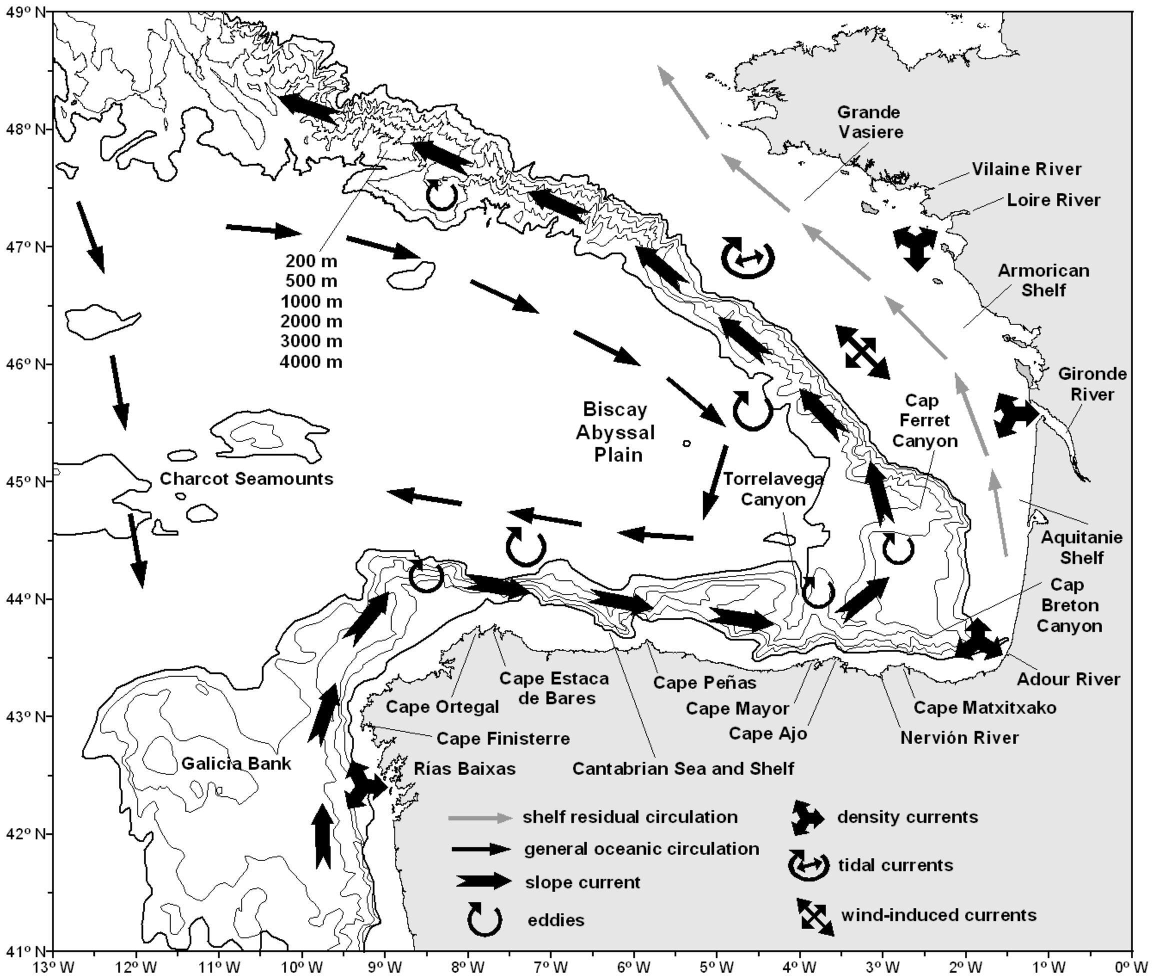

Figure 1. Schematic illustration of the water circulation in the Bay of Biscay (Ferrer *et al.*, 2009).

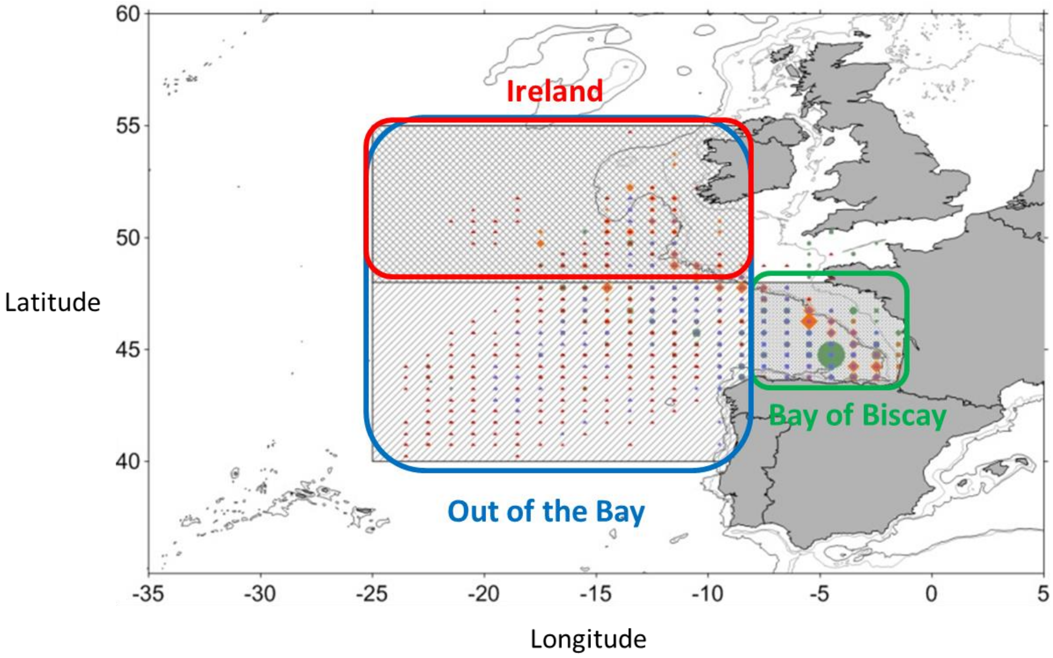

Figure 2. Map showing setting positions carried out by the three fishing gears. The areas highlighted with blue (out of the Bay), Green (in the Bay of Biscay) and red (Ireland) represent the limits considered when building the histograms separated by zones.

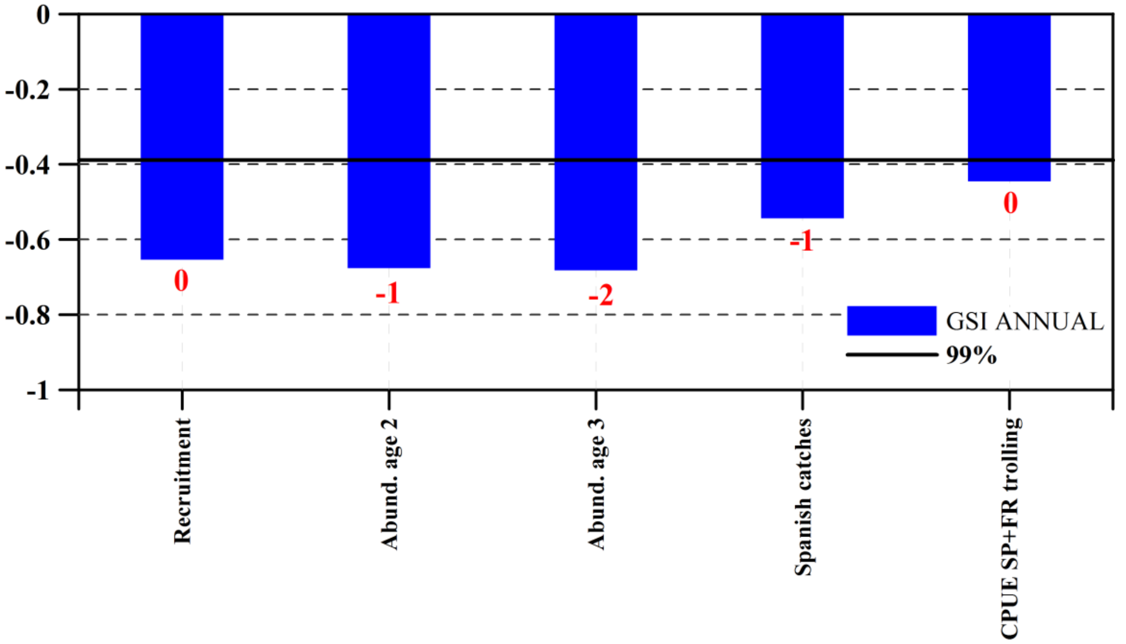

Figure 3. Maximum correlation values and associated time-lags (in red) between the annual GSI index and albacore biological indices such as recruitment, abundance, survival, and total catches and CPUEs.

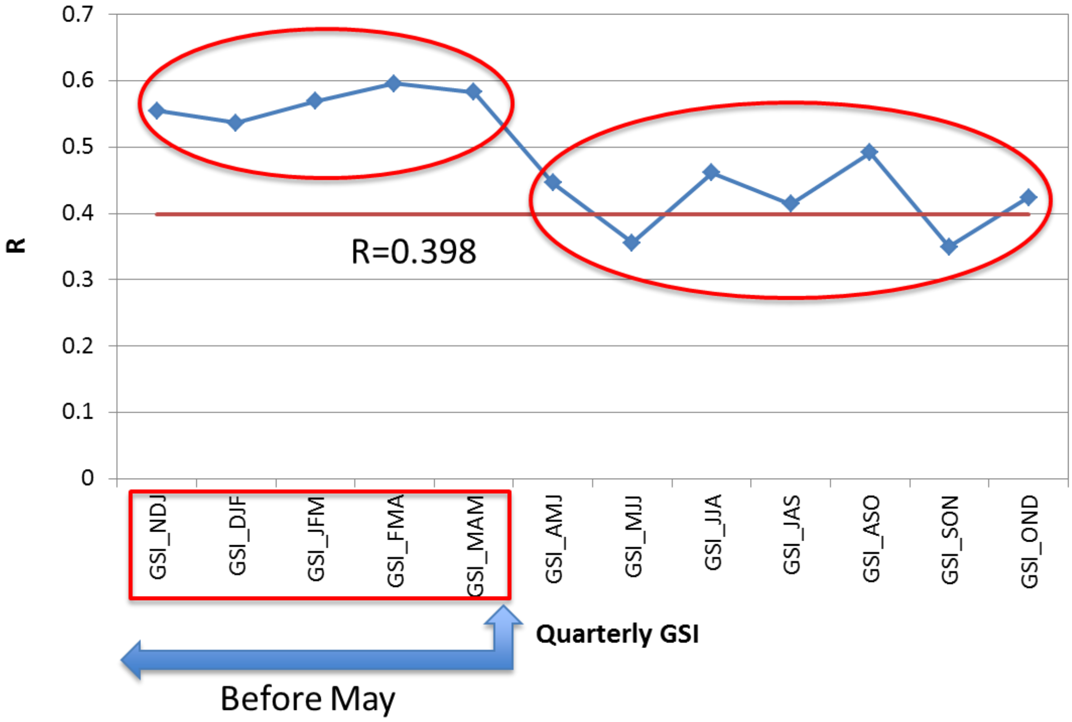

Figure 4. Correlation index between albacore recruitment and quarterly mean values of GSI. The red line represents the value R=0.398, the limit above which the correlations are significant at 99%.

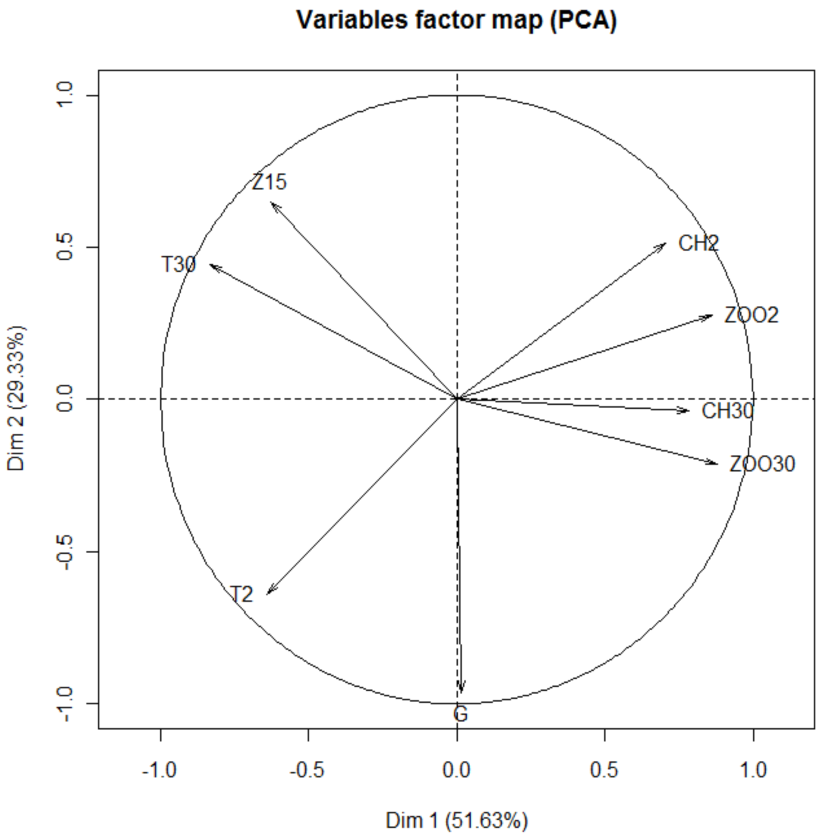

Figure 5. Principal Component Analysis (PCA) of the 10 oceanographic variables extracted from the model ROMS: chlorophyll a at 2 and 30m (CH2 and CH30), zooplankton at 2 and 30m (ZOO2 and ZOO30), temperature at 2 and 30m (T2 and T30), 15ºC isotherm depth (Z15), thermal gradient between the surface and 30m depth (G).

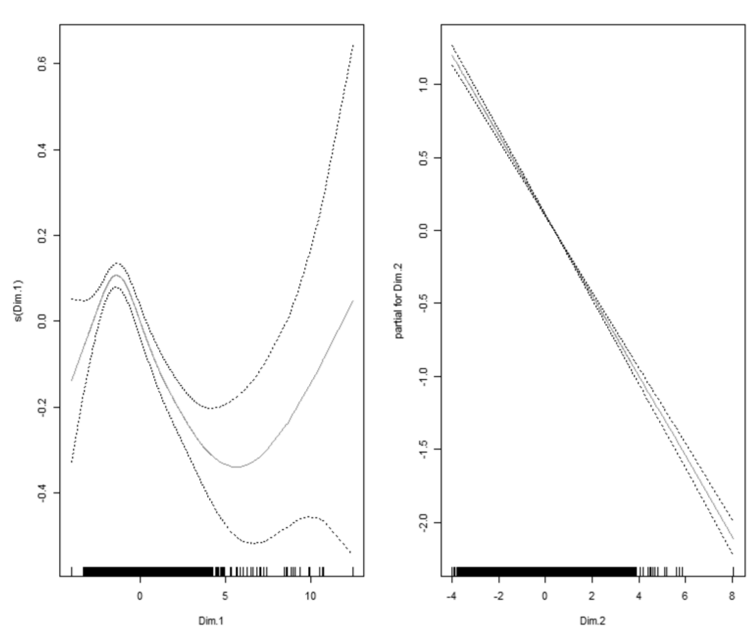

Figure 6. GAMs of daily albacore catches made by baitboat, based on the two first components of the PCA: Dim. 1 (on the left) represents the trophic-thermal component, and Dim. 2 (on the right) represents the stratification level of the water column.

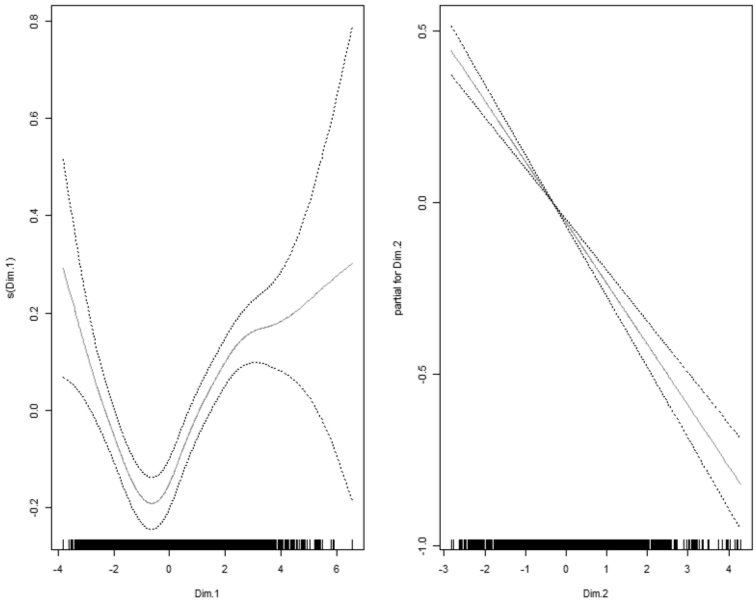

Figure 7. GAMs of daily albacore catches made by trolling line, based on the two first components of the PCA: Dim. 1 (on the left) represents the trophic-thermal component, and Dim. 2 (on the right) represents the stratification level of the water column.

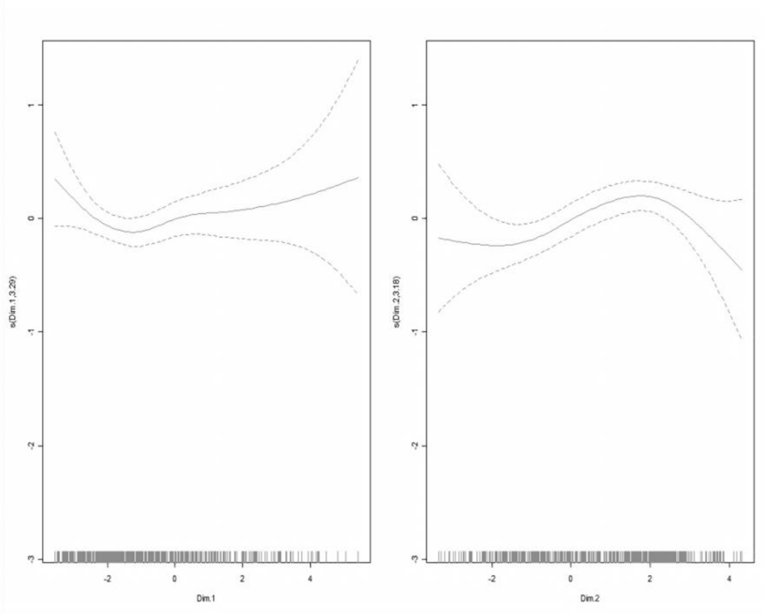

Figure 8. GAMs of daily albacore catches made by pelagic trawling, based on the two first components of the PCA: Dim. 1 (on the left) represents the trophic-thermal component, and Dim. 2 (on the right) represents the stratification level of the water column.

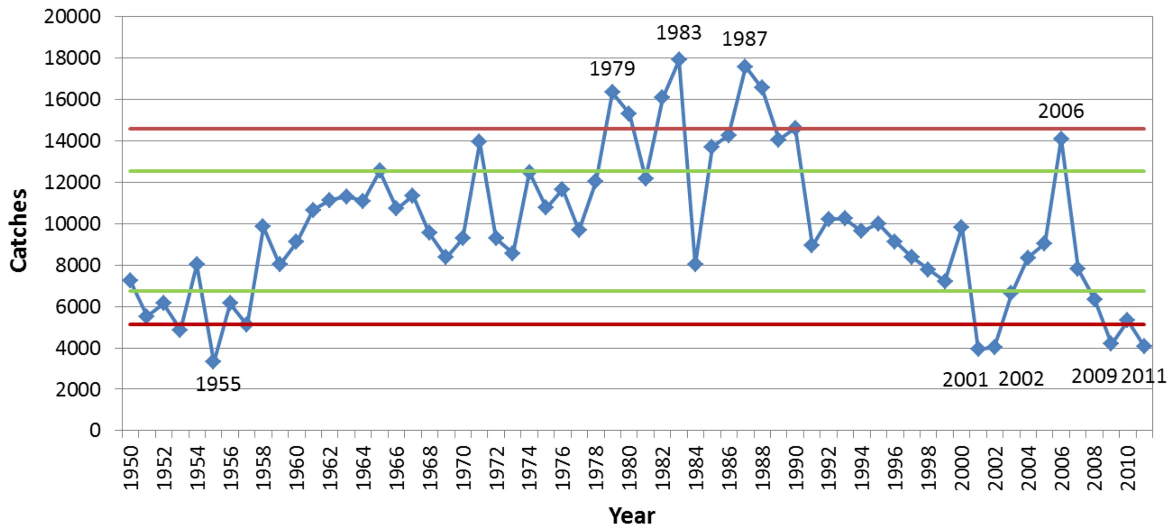

Figure 9. Basque fleet albacore catches (blue line) for the period 1950-2011. Green lines are indicative of percentiles 80% and 20%, whereas red lines represent percentiles 90% and 10%.

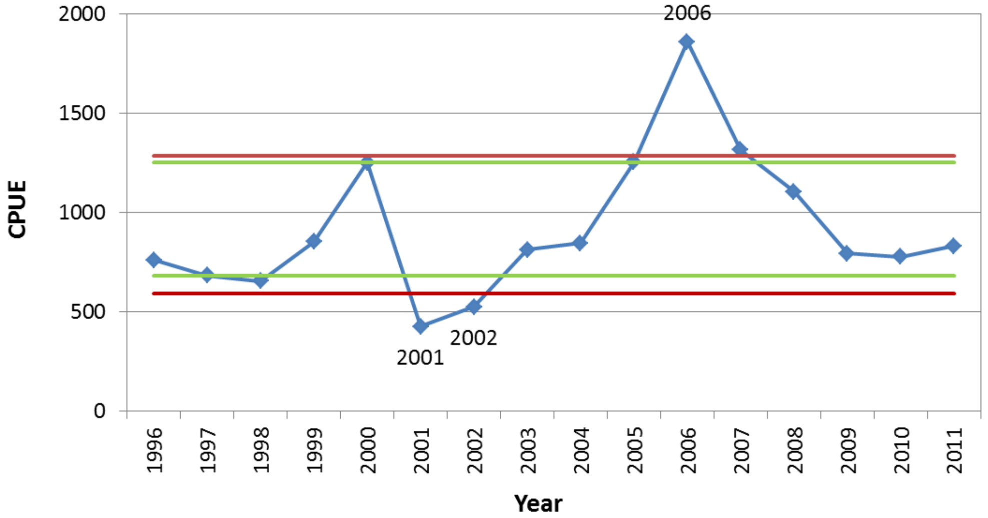

Figure 10. Annual CPUE values for the Basque fleet of baitboat (blue line). Green lines are indicative of percentiles 80% and 20%, whereas red lines represent percentiles 90% and 10%.

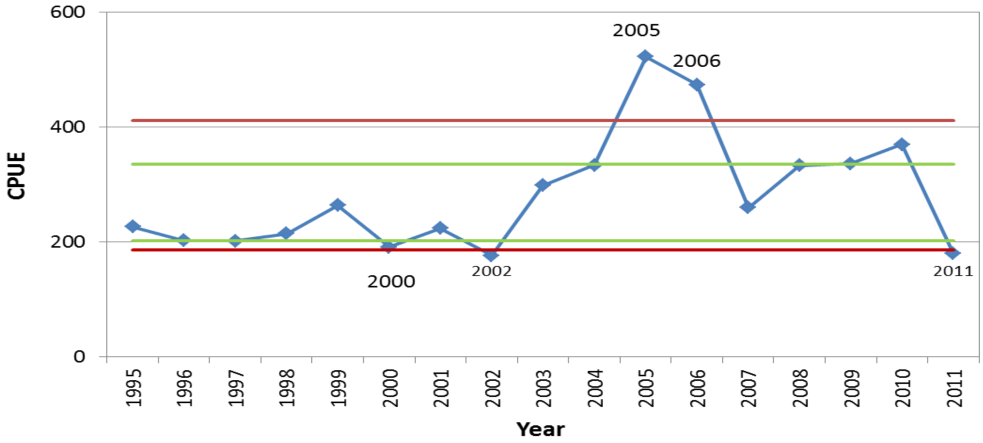

Figure 11. Annual CPUE values for the Basque fleet of trolling line (blue line). Green lines are indicative of percentiles 80% and 20%, whereas red lines represent percentiles 90% and 10%.

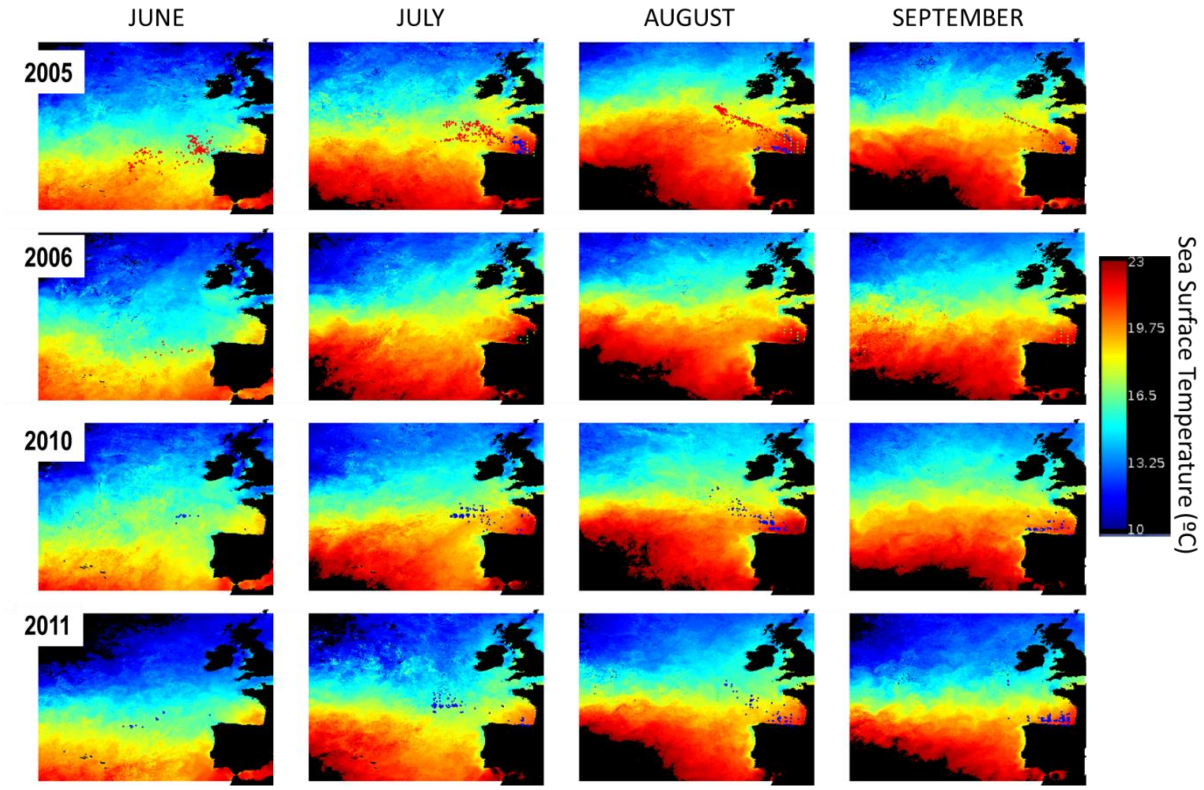

Figure 12. SST maps for the months with higher fishing activity (June, July, August and September) and for years identified as favourable (2005 and 2006) and unfavourable (2010 and 2011) in terms of albacore catches. Dots represent albacore catches by baiboat (blue), trolling line (red) and pelagic trawling (green).

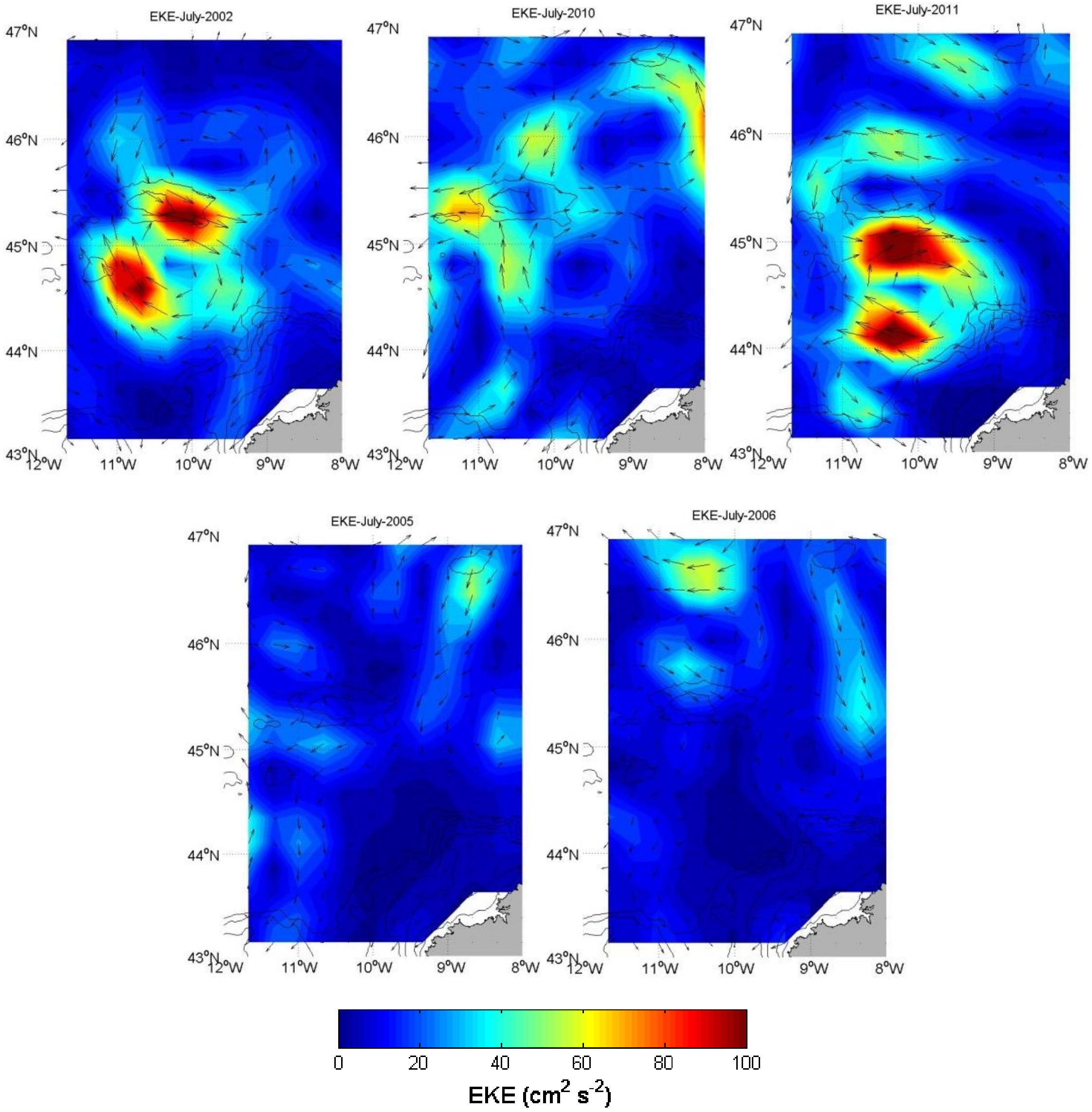

Figure 13. EKE (cm^2/s^2) and associated geostrophic currents (cm/s) in front of the Galician coast for the month of July: above, favourable years 2001 (on the left), 2010 (in the middle) and 2011 (on the right); below, unfavourable years 2005 (on the right) and 2006 (on the left).

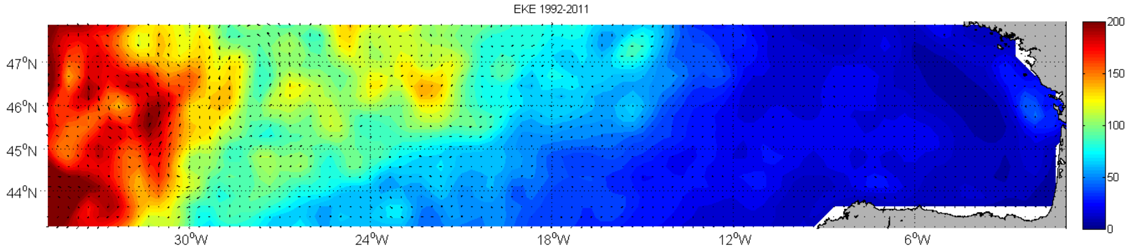

Figure 14. EKE (cm^2/s^2) and associated average geostrophic currents (cm/s) for the period 1992-2011.

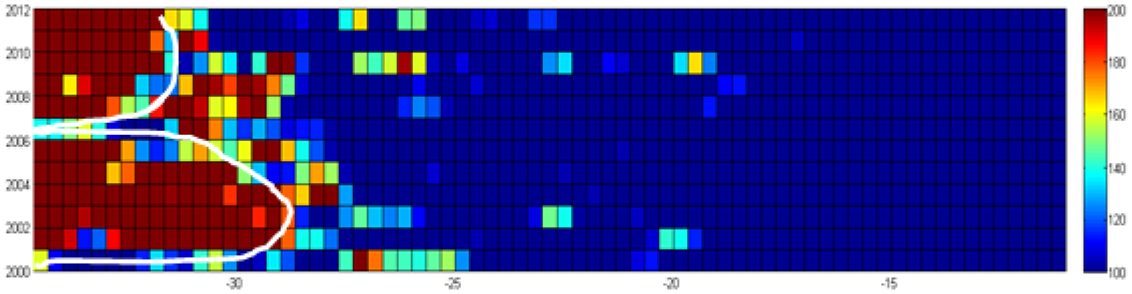

Figure 15. Interannual (2000-2011) and longitudinal variability of mean EKE (cm^2/s^2) for the month of July, out of the Bay of Biscay.