Revista de Biología Marina y Oceanografía
Vol. 46, Nº2: 231-242, agosto 2011
Article

El Niño Southern Oscillation and spatial-temporal variability of the nominal performances of swordfish (*Xiphias gladius*) in the southeastern Pacific

El Niño-Oscilación del sur y la variabilidad espacio temporal de los rendimientos nominales del pez espada (*Xiphias gladius*) en el Pacífico suroriental

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Resumen.- El pez espada (*Xiphias gladius*) es una especie pelágica altamente migratoria, encontrándose en aguas tropicales, subtropicales y templadas. En el Océano Pacífico presenta una distribución latitudinal entre 50ºN y 50ºS, y varios estudios han relacionado su distribución a variables ambientales, ya que el alimento es abundante a lo largo de zonas frontales donde convergen las corrientes o masas de aguas. En el Pacífico suroriental, el anticiclón subtropical fuerza positivamente las temperaturas del océano a lo largo de la costa oeste de América del sur, decreciendo hacia el polo desde las latitudes subtropicales debido al fenómeno El Niño Oscilación del Sur. Ocupando datos ambientales provenientes de sensores remotos, estudiamos los cambios en la posición espacial de la isoterma de 18ºC en relación a los cambios espacio temporal de los rendimientos de pesca nominales (CPUE) de pez espada de la flota palangrera industrial que opera frente a las costas de Chile. Se obtuvieron correlaciones entre el centro de gravedad latitudinal (CGL) de la CPUE y la posición latitudinal de la isoterma de 18ºC; entre la posición latitudinal de la isoterma de 18ºC y el área que limita con la de isoterma de 17ºC y entre el índice El Niño 12 y la posición latitudinal de la isoterma de 18ºC. A nivel estacional, la isoterma de 18ºC se desplaza al sur de los 37ºS a principios de año, hasta alcanzar los 25ºS en agosto. Este patrón ocurre en forma similar con el área delimitada por las isoterma de 17º y 18ºC. Dos fases fueron observadas en la CPUE del pez espada, una con valores de 0,65 ± 0,06 kg por anzuelo registrado desde mediados de abril hasta comienzos de junio, y otra con valores de 0,37 ± 0,05 kg por anzuelo desde comienzo de septiembre hasta finales de noviembre.

Palabras clave: CPUE, isotermas, índice El Niño 12, sensores remotos

Abstract.- Swordfish (*Xiphias gladius*) is a highly migratory pelagic species, found in tropical, subtropical and temperate regions. In the Pacific Ocean, several studies have linked their wide latitudinal distribution (50ºN-50ºS) to environmental variables, since food is abundant along the frontal zones where currents or water bodies converge. In the southeastern Pacific, the subtropical anticyclone positively forces ocean temperatures along the west coast of South America, decreasing pole ward from the subtropical latitudes due to the El Niño Southern Oscillation. Environmental data from remote sensing enabled us to study changes in the spatial position of the 18ºC isotherm in relation to spatial-temporal changes in swordfish nominal fishing yields (CPUE) of industrial longline fleet in the coast of Chile. Correlations were obtained between the latitudinal gravity center (LGC) of CPUE and the latitudinal position of the 18ºC isotherm, between the latitudinal position of the 18ºC isotherm and the area bounded by the 17ºC isotherm, as well as between El Niño 12 index and the latitudinal position of the 18ºC isotherm. At a seasonal level, the 18ºC isotherm moves south of 37ºS at the beginning of the year, reaching 25ºS in August. This pattern occurs in a similar way to the area bounded by the 17º and 18ºC isotherm. Two phases were observed in the swordfish CPUE, with 0.65 ± 0.06 kg per hook since mid-April to early June, and 0.37 ± 0.05 kg per hook from early September until late November.

Key words: CPUE, isotherm, El Niño 12 index, remote sensing

INTRODUCTION

The southeastern Pacific Ocean (SEPO) supports one of the most productive marine systems in the world, the Humboldt Current System (HCS), which involves the coastal upwelling ecosystems in Chile and Peru. There, the upwelling processes of sub-surface waters induced by wind produce nutrient-rich, cold and CO_2 saturated waters, which trigger heat and gas interchange flux between the ocean and the atmosphere (Morales & Lange 2004). In turn, nutrients supplied to the photic zone increase the biological production, which is then transferred through the pelagic food web, exported to the benthic system or accumulated in the sediment. Two large coastal upwelling areas are identified in the HCS off Chile, based on their hydrographic and ecosystem characteristics. The first area is located in the northern area (18-30°S), shows a continuous upwelling (Shaffer *et al*. 1999, Blanco *et al*. 2001), with low levels of chlorophyll-*a*, excluding the more coastal areas (Thomas 1999, Morales *et al*. 2001, Yuras *et al*. 2005). The other, located in the south central area (30-40°S), shows a strong seasonality during spring-summer (Shaffer *et al*. 1999, Thomas *et al*. 2001, Atkinson *et al*. 2002), with high levels of chlorophyll-*a* over a large platform during the upwelling period (Ahumada *et al*. 1991, Thomas 1999, Yuras *et al*. 2005).

According to Longhurst (1998), based on Platt & Sathyendranath (1988) and Sathyendranath *et al*. (1995), the SEPO is classified into three different large systems, regarding three physical-chemical environments or biogeographic units (Fernández *et al*. 2000). The biome of trade winds found in the equatorial region range from 5°S up to the subtropical convergence (~30°S); the west biome, located between the polar front and the subtropical convergence; and the polar biome (Escribano *et al*. 2003). Recent studies on the current system off Chile reinforce these biogeographical units, identifying a zone with low kinetic energy to the north of 29°C, which merges with a weak and persistent wind stress towards the Equator and another zone to the south of 29°C, which involves a high kinetic energy linked to an intense though variable wind stress towards the Equator. These zones are divided by a strong meridional gradient of kinetic energy close to 30°S (Hormazábal *et al*. 2004).

Moreover, the SEPO is characterized by the presence of the subtropical anticyclone and the circumpolar band of low pressure, producing north-south fluctuations in ocean temperature mainly due to changes in atmospheric and oceanographic conditions associated with El Niño Southern Oscillation (ENSO). This atmosphere-ocean coupling significantly reproduces ENSO variability in different temporal cycles and is characterized by a zonal negative pressure gradient in the equatorial Pacific, with east-west wind anomalies, positively forcing ocean temperature anomalies along the west coast of South America, decreasing poleward from subtropical latitudes (Enfield & Allen 1980, Montecinos *et al*. 2003, Montecinos & Pizarro 2005). In this region, sea surface temperature (SST) has a marked seasonality, with maximum values during summer and minimum during winter (Blanco *et al*. 2001).

Swordfish (*Xiphias gladius*) is a highly migratory pelagic species, widely distributed geographically, living in tropical, subtropical and temperate waters (Nakamura 1985, Joseph *et al*. 1994). In the Pacific Ocean, latitudinal distribution between 50°N and 50°S has been reported (Bedford & Hagerman 1983). The zones of greatest presence are areas of high production, such as frontal zones or areas where ocean currents and water masses intersect, creating turbulence and sharp temperature and salinity gradients (Sakagawa 1989, Sosa-Nishizaki & Shimizu 1991, Bigelow *et al*. 1999). Offshore Chile, swordfish is found between 17 and 41°S and from the coast up to 110°W (Yáñez *et al*. 2008, Vega *et al*. 2009), thus covering two of the three major biomes above described in the SEPO. Espíndola *et al*. (2009) identified the existence of a pattern in the spatial and temporal distribution of fishing performances, with high levels between March and July-August, and south-north displacements from 38 to 32°S, and a SST range between 17 and 19°C. Performances subsequently decrease towards the north of 32°S with SST exceeding the 20°C. These results coincide with those described by Yáñez *et al*. (1996), which established swordfish is captured in waters with SST of 14-20°C, with high performances in May (16-18°C) and June (14-17°C).

Studies from other regions of the world have shown a strong relationship between the spatial distribution of swordfish and environmental variables. Bigelow *et al*. (1999) found high catch per unit effort (CPUE) values during spring in the central equatorial Pacific, with an SST of 16-19°C and a strong latitudinal component that increased from 15 to 40°N, unlike the frontal energy, where a reverse effect was observed with high CPUE values as frontal energy decreased. In the Atlantic, Mejuto & Hoey (1991) stated large fish are found in mild zones at high latitudes, while smaller fish show low mobility and their distribution is determined by the seasonal evolution of the SST. Podestá *et al*. (1993) showed swordfish is distributed in waters with SST range between 19-21°C westward of the northern Atlantic, with thermal gradients below the 1°C km^{-1} and distances lower than 40 km from the thermal front. In the subtropical frontal zone of the north central Pacific (STFZ), Seki *et al*. (2002) showed that swordfish is associated to thermal fronts as a physical-biological response, where high CPUE's were observed in areas adjacent to the cold region of the STZF due to an increase in the biological productivity linked to high abundances of squid (*Ommastrephes bartramii*). Association with oceanic fronts has been demonstrated for several pelagic species of tuna, however, in the tropical Pacific there is a permanent zonal displacement of the convergence zone of surface water bodies which act as an aggregating mechanism of plankton and micronekton, and consequently the presence of large predators such as tuna. These zonal displacements of the convergence zone over 50° of longitude occur in phase with the warm and cool phases of the ENSO cycle (Lehodey *et al*. 1997).

According to the antecedents mentioned above, we suggest the spatial and temporal distribution of the nominal performances of swordfish may result from warm and cold phase change of the ENSO cycle, and this might provide a basis tool for the prediction of successful fishing grounds. This hypothesis was verified by correlating observations of temporal series and the latitudinal gravity center of the swordfish CPUE with a proxy of the warm and cold phase of the ENSO cycle, such as the spatial position of the 18°C sea surface temperature (SST) isotherm, and the area delimiting with the 17°C isotherm. Also, El Niño 12 index was used in order to establish that the latitudinal displacement observed in the 18°C isotherm is related with phase change of ENSO cycle. Furthermore, the seasonal pattern of the nominal swordfish CPUE and SST time series was verified.

MATERIALS AND METHODS

Operational data from the industrial longline fleets operating in oceanic waters off Chile between July, 2002 and December, 2007, and up to 110°W and between 17 and 41°S were obtained from the Monitoring Program of Highly Migrating Resources, developed by the Instituto de Fomento Pesquero (IFOP). These records were collected by scientific observers and mostly described and analyzed by Espíndola *et al*. (2009). The data collected include among others, the date and position of deployment and retrieval, number of hooks set, and match in number and trunk weight by species. Since the geographic location of the fishing set is only reported at the beginning and end of the longline deployment and retrieval, the mid-point between the set positions at deployment and retrieval was used. A total of 7091 records were obtained. Regarding this data, 99% fall in the polygon delimited by 19-40°S and 92-76°W (Fig. 1). A latitude-time section was developed for swordfish catches (kg) and fishing effort (hook set), where weekly and every 10 nautical miles latitudes were considered. In order to assess the effect of the 18°C isotherm displacement on the spatial and temporal pattern of the swordfish CPUE, the latitudinal gravity center (LGC) for week *j* for the latitude-time section was used, which give more importance to the latitudes with higher performance, and is defined as:

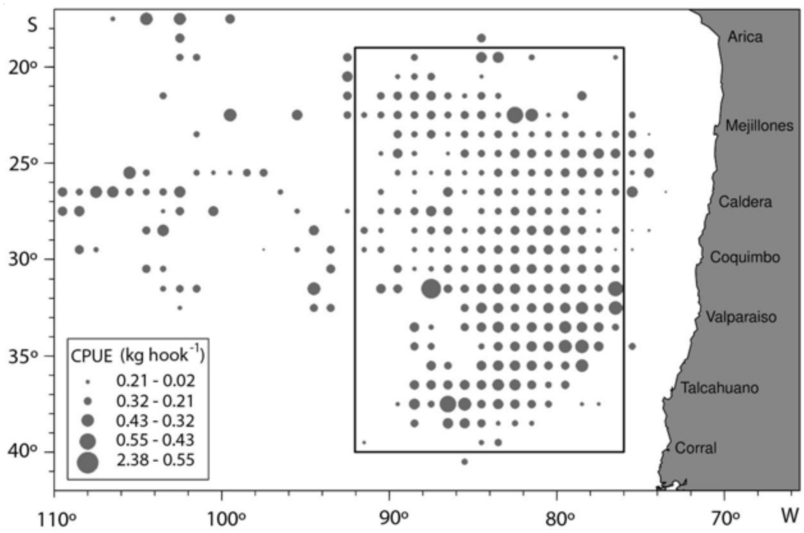

Figure 1. Spatial distribution of the nominal CPUE of swordfish (*Xiphias gladius*) by a one degree grid during the study period and the polygon representing the latitude-time section / Distribución espacial de la CPUE nominal del pez espada (*Xiphias gladius*) por cuadricula de un grado durante el periodo de estudio y el polígono que representa la sección latitud-tiempo

$$CGL_j = \frac{\sum_i L_i \left(C_{ij} / E_{ij} \right)}{\sum_i \left(C_{ij} / E_{ij} \right)}$$

where L_i is the latitudinal component of the i-th observation, C_{ij} is the swordfish catch in the i-th position of week j and E_{ij} is the number of hooks at the i-th position of week j (Lehodey *et al*. 1997). Given the lack of data in the temporal series, seasonality was assessed for the complete period in order to find the mean seasonal value for those weeks where information was not available. A total of 44 records were missing in 287-weeks. This method allowed introducing eleven missing data in the original series and the remaining were interpolated through a cubic spline interpolation.

Daily SST environment databases during the day and night between mid-2002 and late 2007 were collected from Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua standard mapped images (SMI). These data are produced and distributed by ocean color data processing system (OCDPS) from the air space center Goddard at NASA and were downloaded from the Ocean Color portal[1]. The daily images represent a two-dimensional arrangement in an equidistant cylindrical projection, with a spatial resolution of 9.2 km, and were read using the hierarchical data format (HDF) library. The average daily image was estimated using daily images for the day and night and then the weekly average image was assessed. Thus, a total of 287 weeks of satellite images were obtained. In order to avoid absent data in the studied area due to cloud presence and obtain the continuous spatial positioning of isotherms, weekly images were interpolated through an optimal interpolation algorithm (OI) on a two-dimension regular grid using an optiminterp toolbox[2]. This method has been widely used for the reconstruction of oceanographic data (Houseago-Stokes 2000, He *et al*. 2003, Alvera-Azcárate *et al*. 2005), and also in the recovery of sea level anomaly data (Le Traon & Didarboure 1999, Le Traon *et al*. 2001), *in situ* and satellite-derived weather data (Reynolds & Smith 1994) and high resolution weather construction for SST (Reynolds & Smith 1995, Reynolds *et al*. 2002). Once the weekly images were interpolated, the 17 and 18°C isotherms were identified, as well as the mean latitude and the area generated between the 17 and 18°C isotherms. In order to determine the area between the isotherms, the starting and end points inside the 19-40°S;92-76°W polygon were identified; subsequently, all points were united from the beginning of the polygon until generating a sequence of points following the trajectory until the final point was reached, then uniting them to the isotherm points. A set dot was therefore obtained, which gave rise to the polygon given by the isotherm and the studied area margins. Then, the frontal area is given by the difference between the areas generated by the 18 and 17°C isotherms and the area assessment for a set dot matrix defining a spatial polygon given by the formula by Rokne (1996),

$$A = \frac{1}{2} \sum_{i=1}^{n-1} \left(x_i y_{i+1} - x_{i+1} y_i \right)$$

where (x_i, y_i) are the polygon vertexes for $i = 1, \ldots, n$, and where vertexes 1 and n correspond to the same point. This formula assumes identical units for axis x and y (an aspect ratio of 1), as in UTM coordinates (Universal Transverse Mercator). The function automatically converts longitude-latitude coordinates to UTM before calculating the area (Schnute *et al*. 2004).

Statistical analyses of time series were used to study the relations between the LGC of the swordfish CPUE and the latitudinal position of the 18°C isotherm, the latitudinal position of the 18°C isotherm and the frontal area taken up by the 17 and 18°C isotherms and the latitudinal position of the 18°C isotherm as well as the weekly El Niño 12 index[3]. El Niño 12 index is the average SST anomaly in the region bounded by 0-10°S and from 90-80°W. This region lies near the coast of South America and is in phase with the values recorded in other ENSO regions. The cross-correlation function was used to analyze the relations between fisheries and environmental variables. Results are represented by the correlation coefficient between the series, displaced in a determined number of observations or delays. When the expression is assessed for the complete original series, then a cross-correlation series twice the length of the original series is obtained. The environmental and fisheries series were adjusted to the mean seasonal component (weeks) so as to detect the seasonal changes in the analyzed series.

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[1] http://oceancolor.gsfc.nasa.gov

[2] http://modb.oce.ulg.ac.be/mediawiki/

[3] htpp://www.cpc.noaa.gov

RESULTS

A marked seasonality was observed in the studied area regarding the latitudinal displacements of the 18°C isotherm. Such displacements were examined for a warm condition (autumn), when the isotherm locates southward to the 37°S, and a cold condition (spring), when the isotherm locates northward the 25°S, *i.e.*, a displacement of the 18°C isotherm on the order of 720 nautical miles. Under warm conditions, the studied zone was observed to be dominated by waters with an SST above 19°C, a zone distribution of equatorial origin and where high values of swordfish CPUE (~1 kg hook^{-1}) were observed in frontal areas, with low frontal area values (~3.5 10^5 km^2) bounded by the 17°C and 18°C isotherms (Fig. 2). Under cold conditions, low levels of swordfish CPUE (~0.4 kg hook^{-1}) were observed with high frontal area values (~6.3 10^5 km^2) bounded by the 17° and 18°C isotherms. These latitudinal displacements of the isotherms show a strong seasonal variation in their spatial location, where for example during 2003 the industrial longline fleets concentrated their operations southward 36°S during autumn months and northward 26°S during spring. However, during 2007, this industry reached its location to the north of 22°S with the lower temperatures of the studied period.

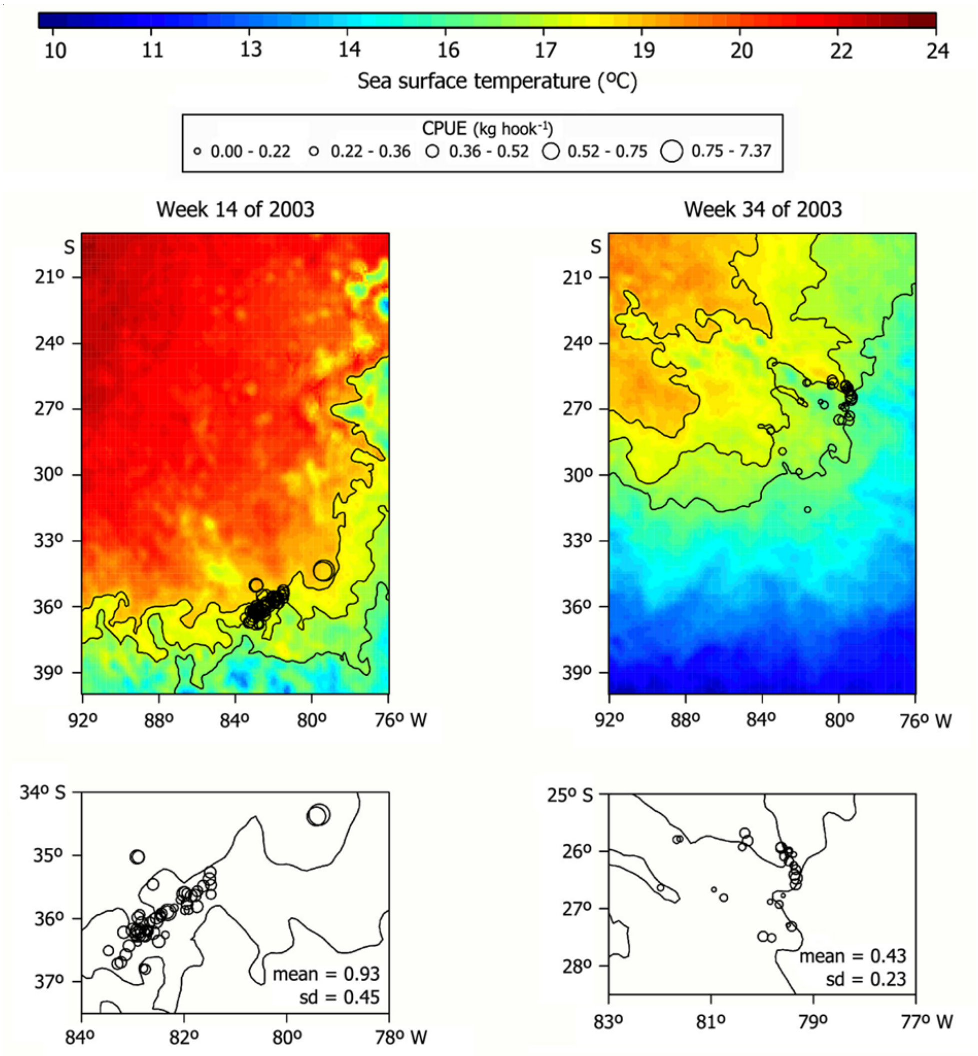

Figure 2. Spatial variability of the weekly average sea surface temperature (MODIS Aqua) associated to the nominal performances of swordfish (*Xiphias gladius*) in the southeastern Pacific Ocean / Variabilidad espacial de la temperatura superficial del mar (MODIS Aqua) promedio semanal asociada a los rendimientos nominales del pez espada (*Xiphias gladius*) en el Océano Pacífico suroriental

The temporal series of the mean position of the 18°C isotherm (Fig. 3) showed a strong predominance of an annual signal and a marked seasonal pattern, where the 18°C isotherm was located north of 24°S (cold months) and was subsequently found south of 36°S (warm months), *i.e.*, with maximum temperatures during austral summer months and minimum temperatures during winter months. Regarding the LGC, this reached the 36°S in March-April and then located at the 24°S by the end of the year. However, when El Niño 12 index reached the highest values during summer-autumn months, the 18°C isotherm was found in its latitudinal position southernmost of the 36°S and when the index reached the lower values during winter-spring months, the 18°C isotherm was found northward of the 26°S, thus showing a reverse relation between both temporal series.

The cross-correlation function between the LGC of the nominal fishing performances and the latitudinal position of the 18°C isotherm showed a 0.65 coefficient with a time lag of 12 weeks, thus observing that the LGC measurements at time *t* + 12 weeks are associated to the 18°C isotherm temporal series at time *t* (Fig. 4a). In the same way, the cross-correlation function between the latitudinal position of the 18°C isotherm and the area delimited by the 17 and 18°C isotherm achieved a value of the 0.78 coefficient with a time lag of zero weeks, thus establishing that the measurements of the temporal series of the latitudinal position of the 18°C isotherm is coupled at zero weeks with the area delimited by the isotherms (Fig. 4b). Finally, the cross-correlation between El Niño 12 index and the latitudinal position of the 18°C isotherm achieved a coefficient value of -0.92, with a time lag of zero weeks, *i.e.*, both series are coupled at the same time but with a reverse pattern (Fig. 4c).

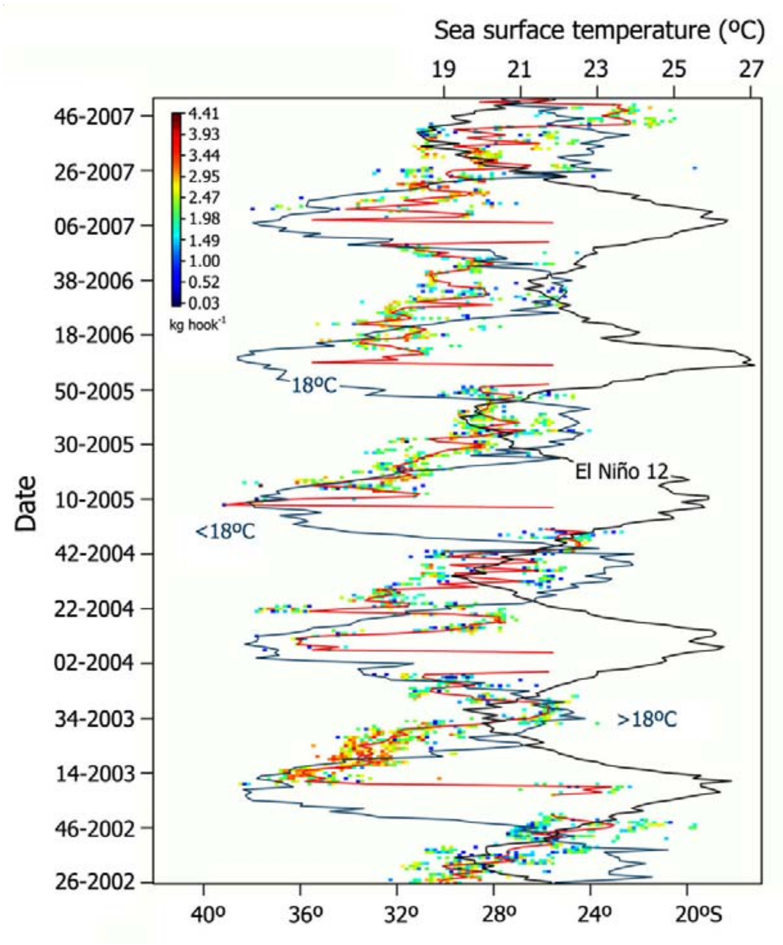

Figure 3. Latitude-time series showing the weekly series for the latitudinal gravity center (LGC: red) of the nominal fishing performances of swordfish (*Xiphias gladius*), latitudinal position of the 18°C isotherm and the El Niño 12 index / Serie latitud-tiempo que contiene las series semanales del centro de gravedad latitudinal (CGL: rojo) de los rendimientos de pesca nominales del pez espada (*Xiphias gladius*), la posición latitudinal de la isoterma de 18°C y el índice El Niño 12

A clear pattern in the latitudinal position of the 18°C isotherm was observed at a seasonal level, with values to the south of the 37°S during the first months of the year, then subsequently moving latitudinally until reaching the 25°S between late September and early October (Fig. 5). This seasonal pattern was strongly coupled to the area delimited by the 17 and 18°C isotherms (Fig. 4b), ranging from 2.1 10^5 km^2 at February to 7.2 10^5 km^2 by late September. The variability observed in the area taken up by the isotherms is directly linked to the frontal energy existing in the studied area. On the other hand, the local relative abundance of swordfish at a seasonal level showed two phases, one where high performances were observed, ~0.65 ± 0.06 kg $hook^{-1}$, which are recorded from week 15 (mid Abril) to 21 (early June), when the 18°C isotherm achieves the latitudinal position of 30°S (Fig. 5). The local relative abundance of swordfish showed a decreasing trend towards the end of the season, when the 18°C isotherm reached the 25°S, with fishing performances close to 0.37 ± 0.05 kg $hook^{-1}$ between week 33 (early September) to week 44 (late November).

DISCUSSION

The identification of significant associations between pelagic species and environmental conditions represents the starting point for the interpretation of the CPUE as an abundance index for highly migratory species, such as swordfish (Brill & Lutcavage 2001, Schick *et al*. 2004). The performance of the industrial longline fleets operating at the SEPO may depend on environmental conditions, influenced by availability (Marr 1951) and vulnerability (Ricker 1975) of the resources to fishing strategies and gear. Our results prove the existence of a large oceanic convergence front in this SEPO zone (Hormazábal *et al*. 2004), which may be significant in keeping the exploited

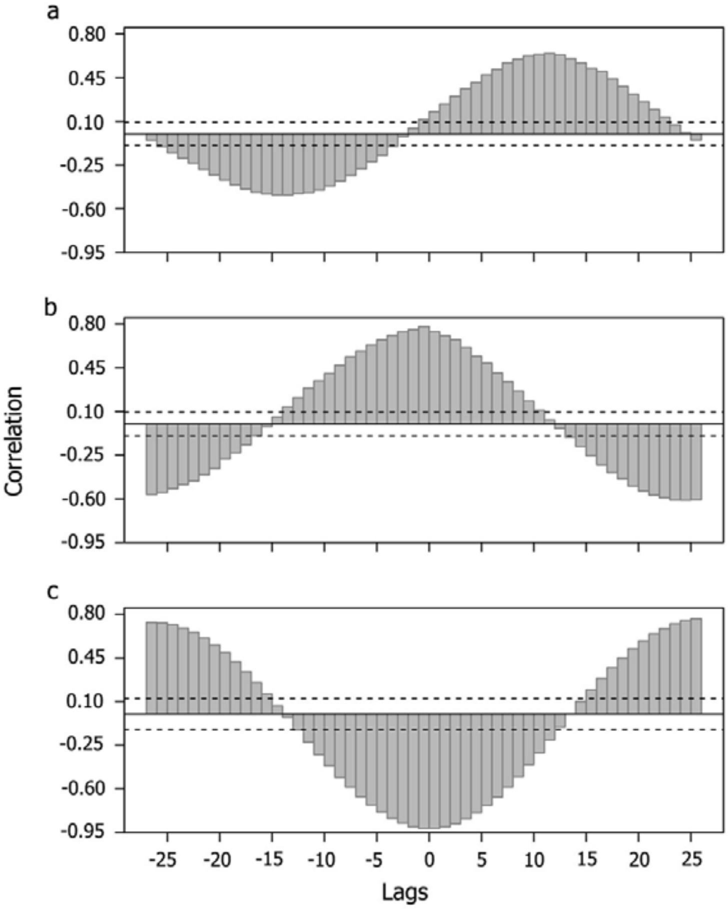

Figure 4. Correlation coefficient between the LGC of the nominal CPUE of swordfish and the latitudinal position of the 18ºC isotherm (a), between the latitudinal position of the 18ºC isotherm and the area delimited by the 17 and 18ºC isotherms (b), the El Niño 12 index and the latitudinal position of the 18ºC isotherm (c), dot lines show the significance of the estimated correlation coefficients / Coeficiente de correlación entre el CGL de la CPUE nominal del pez espada y la posición latitudinal de la isoterma de 18ºC (a), entre la posición latitudinal de la isoterma de 18ºC y el área delimitada por las isoterma de 17º y 18ºC (b), y el índice El Niño 12 y la posición latitudinal de la isoterma de 18ºC (c), las líneas punteadas representan la significancia de los coeficientes de correlación estimados

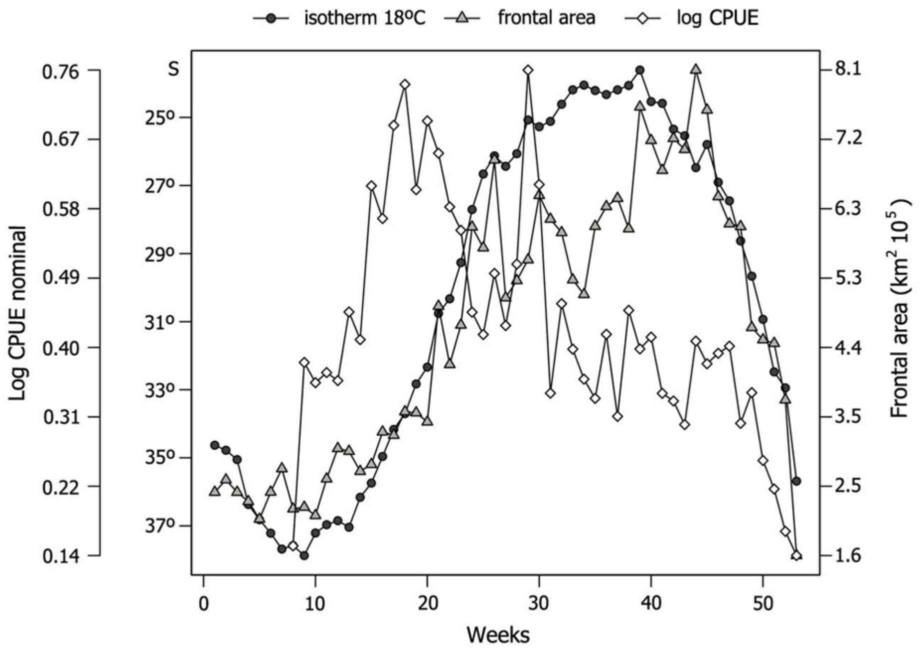

Figure 5. Seasonality (weeks) of the latitudinal position of the 18ºC isotherm, the area delimited by the 17 and 18ºC isotherms and the nominal performances of swordfish (*Xiphias gladius*) in the southeastern Pacific Ocean / Estacionalidad (semanas) de la posición latitudinal de la isoterma de 18ºC, el área delimitada por las isotermas de 17 y 18ºC y los rendimientos nominales del pez espada (*Xiphias gladius*) en el Océano Pacífico suroriental

stock of swordfish in the region. In regards to the latter, considering that the species is abundant in areas of warm and cold current convergence and relatively high primary production, creates conditions capable of supporting large stocks of small pelagic fish predated by swordfish (Podestá *et al*. 1993, Olson *et al*. 1994, Bigelow *et al*. 1999). Ovchinnikov (1971) suggested frontal areas with strong SST gradients, salinity and large biogenic matter, such as the Gulf, Kuroshio and Chile-Peru currents, play a significant role in the distribution of swordfish, and where the habitat selection becomes a crucial factor for the dynamics of the exploited marine populations (Hutchings 1992, Bakun 1996).

Latitudinal displacement of industrial longline fleets performances described in this study has also been observed in the central equatorial Pacific (Bigelow *et al*. 1999). Here, the effort distribution showed a seasonal change as a response to SST and the variations in the SST frontal energy. High CPUE values were observed in the 15-21°C range, with a strong frontal energy in March-May. In our study, the correlation established between the latitudinal gravity center and the 18°C isotherm of 0.64, with a time lag of 12 weeks, suggests that both temporal series follow the same direction but with a gap. The same occurs with the 18°C isotherm and the area delimiting with the 17°C isotherm, which oscillate together with a 0.78 correlation at time lags zero. However, the negative value of 0.92 correlation between El Niño 12 index and the latitudinal position of the 18°C isotherm suggests that high values of the index determine the 18°C isotherm to the south of the 36°S at time lags zero (Fig. 3 and 4). This time lag of months in the time series could indicate that higher swordfish CPUE occurred in decaying and evolving frontal environments. Higher catch rates in decaying frontal environments may indicate that biomass of forage organisms has accumulated through either increased upwelling in a divergent front or concentration in a convergent front (Bigelow *et al*. 1999).

The fluctuations of the latitudinal gravity center of the nominal CPUE of swordfish at the SEPO were observed on an annual scale, reaching a position to the north of the 30°S during the spring-summer months and to the south of the 30°S in autumn-winter. Furthermore, a time lag was observed in relation to the latitudinal displacement of the 18°C isotherm, with values to the north of the 25°S by the late September and to the south of the 37°S by early March. Such interannual fluctuation described by the 18°C isotherm may involve oceanographic processes surrounding the water mass displacement of equatorial origin with a zone orientation

(Blanco *et al*. 2001). Most of these fluctuations have been observed in coastal series off South America in an interannual phase and associated to south El Niño oscillation events (Shaffer *et al*. 1999, Pizarro *et al*. 2002). This oceanographic pattern suggests high swordfish performances occurred in more coastal waters by early April (Fig. 2), due to a higher frontal energy resulting from the reduced area taken up by the 17 and 18°C isotherms, with average values of ~3 10^5 km^2 between early March and mid May (Fig. 5).

The intraseasonal fluctuations of the nominal CPUE of swordfish may be the result of a change in the displacement rate of the latitudinal position of the 18°C isotherm (Fig. 5), probably involving significant population processes such as reproduction, migrations and feeding (Cushing 1975, Sinclair & Tremblay 1984). These processes are the result of the species life cycle adaptation to physical-biological environment seasonality, where favorable habitat selection plays an important role. Such physical-biological coupling may be modulated by intraseasonal fluctuations of the area delimiting the 17 and 18°C isotherms, such as a proxy of the frontal energy at the SEPO. Two phases were clearly observed in the nominal performance of swordfish: high CPUE values with low values of the area delimited by the 17 and 18°C isotherms (high frontal energy) and a latitudinal position of the 18°C isotherm to the south of the 30°S and low CPUE values with high values at the area delimited by the 17 and 18°C isotherm (low frontal energy) and a latitudinal position of the 18°C isotherm to the north of the 30°S (Fig. 5). The mechanisms associated with increased swordfish fishery performance at greater SST frontal energy may not be linked to a preference for SST gradients, especially because swordfish are capable of diel vertical migration through a temperature change of as much as 19°C (Carey & Robinson 1981). Change in water clarity often accompany temperature change across fronts and may provide additional cues to locate fronts (Olson & Podestá 1987).

From a physicist point of view, north of 30°S, low and diffused values in the kinetic energy are observed to the north of the 30°S, with weak and persistent winds for the upwelling; on the other hand, high values in the kinetic energy, closed towards the coast (~600 km), are observed to the south of the 30°S, where wind although stronger remains more variable (Hormazábal *et al*. 2004). The high CPUE values of swordfish to the south of the 30°S may result in the existing high feed concentration generated in the frontal zones, responding to increased lateral and vertical mixing due to the high kinetic energy observed in this area that could stimulate primary and secondary production (Olson & Backus 1985). However, the mechanisms supplying the necessary food biomass for swordfish has not been directly identified (Lehodey *et al*. 1997). Swordfish is an opportunistic predator with a broad trophic spectrum, usually feeding on cephalopods, fish and crustaceans (Bigelow *et al*. 1999, Letelier *et al*. 2009). In the South Pacific swordfish feed particularly on the giant squid (*Dosidicus gigas*), squid (*Todarodes filippovae*), the teleost jellyfish (*Cubiceps pauciradiatus*), and crustaceans. A plausible cause may be both the inflow of warm waters up to 38°S, rich in dinoflagellate populations, and a mixture of nutrients from coastal waters appearing in the southern zone, increase the zooplankton biomass that attracts fishes and squid from which swordfish feeds (de Sylva 1962). This hypothesis is supported by recent studies showing an increase of chlorophyll during winter in oceanic waters (Yuras *et al*. 2005), linked to the coastal upwelling system generated from the frontal density produced by upwelling waters. The propagation of mesoscale eddies offshore increase chlorophyll six months after the spring coastal chlorophyll maximum, a delayed effect of the upwelling increasing chlorophyll beyond the coastal zone during winter, when the coastal upwelling is weaker (Correa-Ramirez *et al*. 2007). This attracts nekton, with a net effect of aggregation of swordfish to forage on the lower trophic level organisms around the eddy edge (Bakun 2006, Fonteneau *et al*. 2008, Mugo *et al*. 2010).

The two phases of relative abundance of swordfish observed in the SEPO and described in this study may be associated to the existence of three physical-chemical environments and geographical units (Fernández *et al*. 2000, Escribano *et al*. 2003): the biome of trade winds found in the equatorial region, varying from 5°S up to the subtropical convergence (~30°S), with low values for the Coriolis parameter, weak seasonality in wind stress and low levels of relative abundance for swordfish; and the west biome, located between the polar front and the subtropical convergence, with large seasonal differences in the mixing layer forced by seasonality in the surface irradiance and wind stress, with a strong seasonality of spring bloom and high levels of relative abundance of swordfish. The coupling of population biological processes with physical-biological processes in the environment would support the hypothesis that in the SEPO area swordfish would make an annual migration, conducted by feeding and reproduction processes.

Migration involves movements towards cold waters to feed by late summer and a progressive movement towards the north to warm waters to finally return to oceanic warm waters in spring for spawning (Zárate 1997, Espíndola *et al*. 2009, Vega *et al*. 2009). This pattern has already been described for this species, although mainly for the Atlantic (Nakamura 1985, Mejuto & Hoey 1991).

Finally, along the west coast of South America, the interannual variability of SST decrease polewards from the tropics and is mainly related to the ENSO cycle (Enfield & Allen 1980, Montecinos *et al*. 2003). Furthermore, this atmosphere-ocean coupling reproduces ENSO-like variability at different time cycles (Montecinos & Pizarro 2005). The observed changes in El Niño 12 index can be effectively used as a proxy for predicting the spatial distribution and relative abundance of swordfish in the SEPO, with spatial distribution consequences of swordfish aggregations and the longline fleet that operates in this part of the SEPO. This may also allow for the identifying of changes in the local abundance due to movements to other areas and abundance changes caused by the direct impact of exploitation.

The present study concludes that the horizontal distribution of swordfish is influenced by both temporal and spatial environmental conditions, *i.e.*, the latitudinal displacement of industrial longline fleet performances follows the latitudinal displacement of the 18°C isotherm. Furthermore, two phases were clearly observed in the nominal performance of swordfish: high CPUE values to the south of the 30°S and low CPUE values to the north of the 30°S. Finally, mesoscale features such as eddies should play a relevant role in increasing the catches of swordfish since eddies could optimize enrichment and concentration processes. This fact is considered to be one of the major issues in determining whether the high yields of swordfish are associated to the concentration of food or else to particularly favorable environmental conditions in the southeastern Pacific.

ACKNOWLEDGMENTS

We would like to thank Mr. Rodrigo Vega for his valuable advice and for providing such useful comments on earlier versions of this manuscript. We are also grateful to the NASA Goddard Space Flight Center for sharing with us the Aqua-MODIS sea surface temperature data sets that we could downloaded from the Ocean Color portal (http://oceancolor.gsfc.nasa.gov). Finally, we would like to thank the Monitoring Program of Highly Migrating Resources, developed by the Instituto de Fomento Pesquero (IFOP) for the valuable information gathered by scientific observers on the operation of the Chilean longline fleet working in the southeastern Pacific.

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Received 21 December 2010 and accepted 28 June 2011