

Research Article

Identification of the spatial-temporal distribution pattern of swordfish (*Xiphias gladius*) in the southeastern Pacific

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ABSTRACT. The pattern of the spatial-temporal distribution of the fishing yields (catch rates) of swordfish (*Xiphias gladius*) from the Chilean industrial longline fleet it was determined using generalized additives models, autocorrelation analysis and Fourier spectral analysis. The basic information came from fishing log-book recorded by scientific observers between January 2001 and December 2005. The generalized additives models included five physical variables (latitude, longitude, date, lunar index and sea surface temperature (SST)), which affect the availability and vulnerability of swordfish, and two operational variables (length of the vessel and type of longline), which are directly associated with the effectiveness of the fishing system. The non-linear effects were established significantly ($p < 0.01$) for each of the independent variables. There was a typical annual cycle in the catch rates, with high values from March to July/August, and displacement of the fishing operation northward from the 38° to 32°S, in a SST range of 17° to 19°C. Subsequently, catch rates decrease in a northerly direction from 32°S in SST higher than 20°C. This spatial-temporal pattern was determinates with a high square coherency (79%) in the time series of nominal catch rates and latitudinal component analyzed in the Fourier spectral analysis. It also established for the time series of swordfish nominal catch rates, low-frequency fluctuations with periods of 28, 38 and 59 days. This intraseasonal variability in swordfish catch rates coincides with changes in mesoscale oceanographic conditions in the area where the fishery is developed off the coast of Chile.

Keywords: *Xiphias gladius*, pelagic longline, SST, spatial-temporal pattern, southeastern Pacific.

Identificación del patrón de distribución espacio-temporal del pez espada (*Xiphias gladius*) en el océano Pacífico suroriental

RESUMEN. Se determinó el patrón de distribución espacio-temporal de los rendimientos de pesca (tasa de captura) de pez espada (*Xiphias gladius*) de la flota palangrera industrial chilena, mediante el uso de modelos aditivos generalizados, análisis de autocorrelación y análisis espectral de Fourier. La información base provino de bitácoras de pesca registradas por observadores científicos entre enero de 2001 y diciembre de 2005. En los modelos aditivos generalizados se incluyeron cinco variables físicas (latitud, longitud, fecha, temperatura superficial del mar (TSM) y el índice lunar), que afectarían la disponibilidad y vulnerabilidad del pez espada, y dos variables operacionales (largo del barco y tipo de palangre), que se asociarían directamente con la efectividad del sistema de pesca. Los efectos no lineales fueron establecidos significativamente ($p < 0,01$) para cada una de las variables independientes. Se observó un ciclo anual característico en la tasa de captura, con valores elevados de marzo a julio-agosto, y desplazamientos de la operación de pesca de sur a norte de 38° a 32°S, en un rango de TSM de 17° a 19°C. Posteriormente, los rendimientos disminuyeron en dirección norte desde los 32°S con TSM mayores a 20°C. Este patrón espacio-temporal fue determinado con una alta coherencia cuadrada (79%) en las series temporales de las tasas de captura nominal y la componente latitudinal analizadas en el análisis espectral de Fourier. Además, para la serie temporal de la tasa de captura nominal se establecieron fluctuaciones de baja frecuencia con períodos de 28, 38 y 59 días. Esta variabilidad intraesta-

cional en la tasa de captura coincide con las variaciones en las condiciones oceanográficas de mesoescala en la zona donde se desarrolla la pesquería frente a la costa de Chile.

Palabras clave: *Xiphias gladius*, palangre superficie, TSM, patrón espacio-temporal, Pacífico suroriental.

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INTRODUCTION

Migrations in populations have been described as persistent movements by the animals from one habitat to another (Dingle, 1996). Nakamura (1969) describes two types of migrations for highly migratory species: one that is passive, which is the movement within a habitat in response to local biotic and abiotic conditions, and one that is active, in which the fish move from one habitat to another, following an ontogenetic change resulting from a biological requirement motivated by the need to feed and reproduce. Carey & Robinson (1981) and Carey (1990) showed the first type of movement for swordfish (*Xiphias gladius*) in telemetric studies of their vertical migration, which indicate that the swordfish remain at depths of 400 to 600 m during the day and come to the surface (0-100 m) to feed at dusk. With respect to larger movements, Seki *et al.* (1999) report a reproductive migration by swordfish populations from the north to the south Pacific in spring-summer. Bigelow *et al.* (1999) integrated fishery and oceanographic information from the central north Pacific, concluding that the geographic distribution of the fishing effort on swordfish varies seasonally in response to the movements of certain isotherms and the frontal energy in the sea surface temperature (SST). Labelle (2002) mentions year-round north-south migrations for the Japanese longline fishery in the North Pacific ocean but no east-west migration; the same situation is reported for the Atlantic (Berkeley, 1990).

The explicit effects of fish mobility and the importance of environmental factors in the distribution of fishery resources are generally ignored in stock assessment models and fishery management policies (Sharp *et al.*, 1983; Kawasaki *et al.*, 1991). When fishing is distributed uniformly over the distribution area, such movements may not be relevant for the population dynamic models (Beverton & Holt, 1957; Hilborn & Walters, 1992). On the other hand, with highly migratory species and when fishing is not distributed uniformly over the distribution area, ignoring these movements can cause errors in the estimates of the exploitation rates (Bertignac *et al.*, 1998; Silbert *et al.*, 1999; Lehodey, 2001); these estimates are critical

for robust stock assessments (Brill & Lutcavage, 2001).

The nominal catch per unit effort (CPUE) can be interpreted as the success of the fishing in the fishery statistics (Ricker, 1975). As a fishery performance index, it is often used to indicate changes in the abundance of exploited marine populations (Bigelow *et al.*, 1999; Perry *et al.*, 2000). Changes in spatial distribution or availability of the fish to the fishing gear or devices are behavioral responses that can occur on different time scales, thereby confusing the abundance estimates. Understanding the variations in the CPUE on shorter time scales than the time required to generate a fish population could indicate how the animals respond to processes that occur on other temporal scales and, thus, help improve abundance estimates (Perry *et al.*, 2000). In stock assessment models (dynamic population models), catchability, the main parameter relating the CPUE with stock abundance, is defined as a measure of the interaction between resource abundance and the fishing effort (Arreguin-Sánchez, 1996; Perry *et al.*, 2000); it is usually considered to be constant. Although this value can vary according to temporal and spatial scales, these variations can reflect changes that occur on different scales due to changes in the physical environment, the biological environment (such as fish behavior), or in a physical-biological coupling.

Swordfish are a highly migratory, oceanic, pelagic species inhabiting surface waters over 13°C, although they can enter colder waters seasonally (Nakamura, 1985). Swordfish are abundant in high production areas such as frontal zones or areas where oceanic currents or water masses intercept, creating turbulence and marked temperature and salinity gradients (Sakagawa, 1989; Sosa-Nishizaki & Shimizu, 1991; Bigelow *et al.*, 1999). In the southeastern Pacific ocean, swordfish are commercially exploited in the oceanic zone – whether as a target species or by-catch – by industrial fleets from a variety of countries such as Japan, Korea, Taiwan, EC-Spain, and Chile (Barbieri *et al.*, 1990; Weidner & Serrano, 1997; Ward *et al.*, 2000). Given that the swordfish catches recorded in the eastern Pacific ocean totaled 15,298 metric tons in 2003 (CIAT, 2005) and the fishery's high economic

value, swordfish population management has been the topic of intense debate and international effort since the 2000. Monitoring pelagic species that are widely distributed in space is inherently difficult and understanding the behavior of the spatial and temporal variations in the catch rates is an important component that would improve stock assessment models, helping establish fishery management policies.

In this study, we establish the operational and environmental variables that contribute to the variability in the performance of Chilean industrial longline swordfish fishery through the use of generalized additive models. Moreover, the spatial-temporal distribution pattern was identified for the nominal catch rates of swordfish in the southeastern Pacific off the coast of Chile on different temporal scales. To achieve this, we studied daily time series of the nominal CPUE and the latitudinal component of the geographic position of the fishing sets through an autocorrelation analysis and Fourier spectral analysis.

MATERIALS AND METHODS

Operational data for Chilean industrial longline fleet fishing in the oceanic waters off Chile (southeastern Pacific to 110°W and between 17° and 41°S) during the 2001 to 2005 fishing seasons come from the Monitoring Program for Highly Migratory Resources developed by the Instituto de Fomento Pesquero (IFOP). The data collected by scientific observers include among others, the date and position of deployment and retrieval, number of hooks set, sea surface temperature (SST), and catch in number and trunk weight by species. During the studied period, a total of 14 vessels, ranging in length from 17 to 54 m and averaging 28 m, were operated; these completed a total of 8,075 fishing sets. The relative swordfish abundance index corresponded to the nominal CPUE, calculated in terms of the weight of the specimens (kg) per hook set.

Since the geographic location of the fishing set is only reported at the beginning and end of the longline deployment and retrieval, the geometric shape (circular, zigzag, spiral, etc.) of the each particular set is not known. Thus, the mid-point between the set positions at deployment and retrieval was used. The same is true for the location of the catch along the longline, which generates a radius of uncertainty on the order of 22-38 km, these values correspond at the half of the values observed at the first and third quartiles for all lengths of longline set.

Due to the uncertainty in the geographic location of the catch and the fact that the SST used in the analysis was recorded by the boat sensors at the beginning of the deployment, the relationships between the environmental variables and the CPUE were established on the mesoscale level (18-100 km). The variables considered in the analysis were: 1) latitude (°), 2) date of the set as a continuous series, 3) length of the boat (in meters), 4) SST at the beginning of the setting (°C), 5) longitude (°), 6) lunar phase, determined as an index based on the percentage of illumination from the moon, and 7) type of longline used for the set (American or Spanish).

The lunar index was included in the analysis since it could influence the availability of swordfish at a given depth (Carey & Robinson, 1981) as well as its vulnerability to the fishing gear (Draganik & Cholyst, 1988). Each lunar orbit ranged from not illuminated to partially and completely illuminated, returning to partially and then completely not illuminate. This cycle is a continuous process in which eight distinct stages, or “lunar phases”, are distinguished. The lunar index was calculated for each day of fishing in the analyzed time period, with values ranging from 0 (new moon) to 7 (full moon). This index was estimated using the astronomic algorithm for the calculation of the lunar phase (Meeus, 1991). The longline type refers to the construction material, design, and dimensions of the fishing gear: American longlines use a nylon monofilament rope in the mainline and leader (18-20 m long), whereas Spanish longlines are made of multifilament ropes, with shorter gangions, and have, on the distal part of the leader, a section of 3 to 7 strands steel wire.

The functional relationships between fishing yield and the environmental conditions are generally non-linear (Kareiva, 1990; Maury *et al.*, 2001). Generalized additive models (GAM) have been used to identify the variables that affect catch rates, moreover allowing the determination of the nature of the relationships. GAMs are non parametric generalizations of multiple lineal regressions, without suppositions as to the functional relationships between the predictors and the response variable (Hastie & Tibshirani, 1990). The non linear components of the relationships were fit with a spline smoother (Hastie, 1992); the “span” or size of the neighborhood of the spline smoother determined the fraction of the data used for smoothing each point. The significance of the adjusted model was evaluated through the contrast in the reduction of the residual variance of the GAM, with respect to a theoretical model with linear terms.

To develop the GAM, we followed a similar procedure for fit and applied the test described by Bigelow *et al.* (1999). The link function that relates the expected value of the response variable (nominal CPUE for swordfish) with the predictors is modeled as the sum of the spline functions of the variables being studied. Considering that the frequency distribution of the response variable is a Gama-type, we applied a

$$\log(\text{CPUE} + c) = a + s(\text{Latitude}) + s(\text{Date}) + s(\text{Length}) + s(\text{SST}) + s(\text{Longitude}) + s(\text{Lunarindex}) + s(\text{Longlinetype}) + e$$

where c and a are constants, e is the random error, and s represents the spline smoother of the independent variables. The construction of the model was done by successively entering variables into a model without predictive variables, or a null model (forward selection). In each stage of the model construction, the Akaike Information Criterion (AIC) was calculated for each model, adding a candidate variable until obtaining the model with the lowest AIC value. The goodness of fit of the non parametric model was evaluated in terms of the pseudo coefficient of determination ($Pseudo - r^2$) (Swartzman *et al.*, 1992), given by:

$$Pseudo - r^2 = 1 - \frac{\text{deviance}_r}{\text{deviance}_n}$$

where “deviance” is defined as the quality of the fit for a statistical model (similar to the coefficient of determination (r^2) for a common sum of squares) used to test the statistical hypothesis in generalized models (additive or linear). This is defined as:

$$D(y, \theta) = -2 \log [p(y|\theta)]$$

where θ are the parameters corresponding to the distribution of the variable y . This expression can be read simply as minus two times the logarithm of the maximum verisimilitude of the adjusted model. According to the results obtained in the GAM analysis, we determined the characteristic seasonal scales of variability for the CPUE time series and the latitudinal component of the fishing operation so as to be able to infer a spatial-temporal pattern in the swordfish fishing yields. This required building time series (daily) of the nominal CPUE and the latitudinal component of the geographic position of the catches for the period analyzed, averaging the values for each fishing day. We used the auto-correlation function at different lags k ; this is defined as:

$$\rho(k) = \frac{\gamma(k)}{\gamma(0)} = \frac{\gamma(k)}{\sigma_x^2}$$

logarithmic transformation to normalize this and comply with the suppositions of the GAM. Furthermore, a constant that represent 10% of the average value of the nominal CPUE was added to all the observed values; this avoided the problem of data near zero. Seven independent variables were included in the model, such that:

where σ_x^2 is the variance of time series x_t and $\gamma(k)$ defines the function of auto-covariance, given by:

$$\gamma(k) = E(x_t - \mu)(x_{t+k} - \mu)$$

where μ is the average of the series x_t and k is the lag. According to Perry *et al.* (2000), the auto-covariance or auto-correlation function should be calculated between observations at different time lags in order to identify the seasonal scales on which the data series became uncorrelated, the time scales on which the function of auto-correlation crossed the value zero, or when it reached the mean level of auto-correlation in the series (for those series which had no zero crossing). The maximum number of lags selected was 110 days, since this value incorporates variations on a seasonal scale.

Later, the time series were analyzed in the domain of the frequency using Fourier spectral analysis (Bendat & Piersol, 1971; Priestley, 1981; Shumway & Stoffer, 2006) in order to determine the cyclic patterns in the time series. This method describes how the energy (variance) of a time series is decomposed into particular frequencies. This decomposition is based on a series of sinusoidal functions (sines and cosines) of particular wave lengths, based on the functions of the harmonic model that expresses the periodic function of the time series as the sum of the sinusoid and the cosinusoid, defined as follows:

$$x_t \approx \sum_{j=1}^J A_j \cos(2\pi f_j t) + B_j \sin(2\pi f_j t)$$

where A_j and B_j are the random Fourier (series) coefficients, the f_j are the fundamental frequencies or the harmonics. This approximation of time series x_t as a Fourier series could be re-expressed in complex exponential form, such that:

$$x_t = \sum_{j=-J}^J C_j e^{i2\pi f_j t}$$

where the values C_j are the complex random Fourier coefficients that have zero mean. The exact approximation of the previous equation is an integral known as the spectral representation of x_t . The spectrum or spectral density $S(f)$ for series x_t can be described in terms of the coefficients of C_j , such that:

$$S(f_j) = E|C_j|^2$$

Thus, the value of the spectral density at frequencies f_j is the second moment of the random amplitude

$$K(f_j) = \frac{|S_{xy}(f_j)|^2}{S_x(f_j)S_y(f_j)} \approx \frac{|EC_{xj}C_{yj}|^2}{E|C_{xj}|^2 E|C_{yj}|^2} = |\text{corr}(C_{xj}, C_{yj})|^2$$

This approach is the most natural interpretation of the squared coherence, given by the squared correlation between random coefficients C_{xj} and C_{yj} of series x_t and y_t at frequencies f_j (Mathsoft Inc., 2001). This bivariate spectral analysis is used to calculate and graph the spectra of squared and phase coherence (cross-spectrum angle) between the swordfish nominal CPUE and the latitudinal component of the geographic position of the fishing set. All the figures and statistical analyses done in this work were implemented using R programming language and statistical computation (R Development Core Team, 2006).

RESULTS

The fishing sets of the longline swordfish fleet carried out from 2001 to the end of 2005 were distributed between 17°S and 41°S and from the coast to 110°W (Fig. 1a). The annual cycle of the catch rates, both in the latitudinal and the longitudinal components, showed a defined spatial pattern that increased in the case of the latitude, beginning with its southernmost location in March (41°S) and then moving northward until reaching 17°S in February (Fig. 1b). On the other hand, the longitudinal component from March to December presented scant east-west variability, and on average, most of the fishing sets were distributed between 80° and 85°W (Fig. 1c). The fishing sets for the analyzed period delimit a polygon that includes a spatial distribution area on the order of 402 square degrees, with a clear south to north orientation during a large part of the year, except in January and February, when the longline fleet is distributed to the west of 90°W (Fig. 1d).

A compound graph showing how the fishery performance (nominal CPUE) varies as a function of time, latitude, and SST (Fig. 2) was generated by cal-

culating the logarithm of the average CPUE for each 10 nm of latitude between 41° and 17°S and the average weekly SST from the first week of January 2001 to the last week of December 2005. The average SST shows warm periods (maximum SST) in summer and cold periods (minimum SST) in winter, revealing an annual SST cycle in the southeastern Pacific ocean.

The nominal fishing yields were greater from March through July-August every year (Fig. 2). During this period, the nominal CPUE moved from 38° to 32°S, in water masses with temperatures between 17 and 19°C, reaching yields with values over 1 kg per hook. Later, the fishing yields dropped drastically to levels as low as 0.1 kg per hook north of 32°S in SST higher than 20°C. A general tendency in the thermal habitat of the swordfish was observed in the southeastern Pacific; the catch rate tended to drop with the onset of the spring-summer SST heating cycle and to increase when the SST cooling cycles began (Fig. 2).

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Generalized Additive Model (GAM)

In the development of the GAM, a total of seven explanatory variables with a high statistical significance and P -values extremely small (Table 1) were selected. All the variables selected presented significant reductions in the residual deviance, which decreased rapidly as the number of variables increased; this was evident until the sixth variable (Table 1). On the other hand, the pseudo coefficient of determination increased at decreasing rates with the number of variables until reaching its maximum value. Latitude was the most significant variable related to the variability in the nominal swordfish CPUE, explaining 53% of the deviance (Table 1). The variables date and length of boat followed distantly, with each variable explaining only 13% of the deviance. Finally, the SST, longitude, and lunar index each explained approximately 7% of the

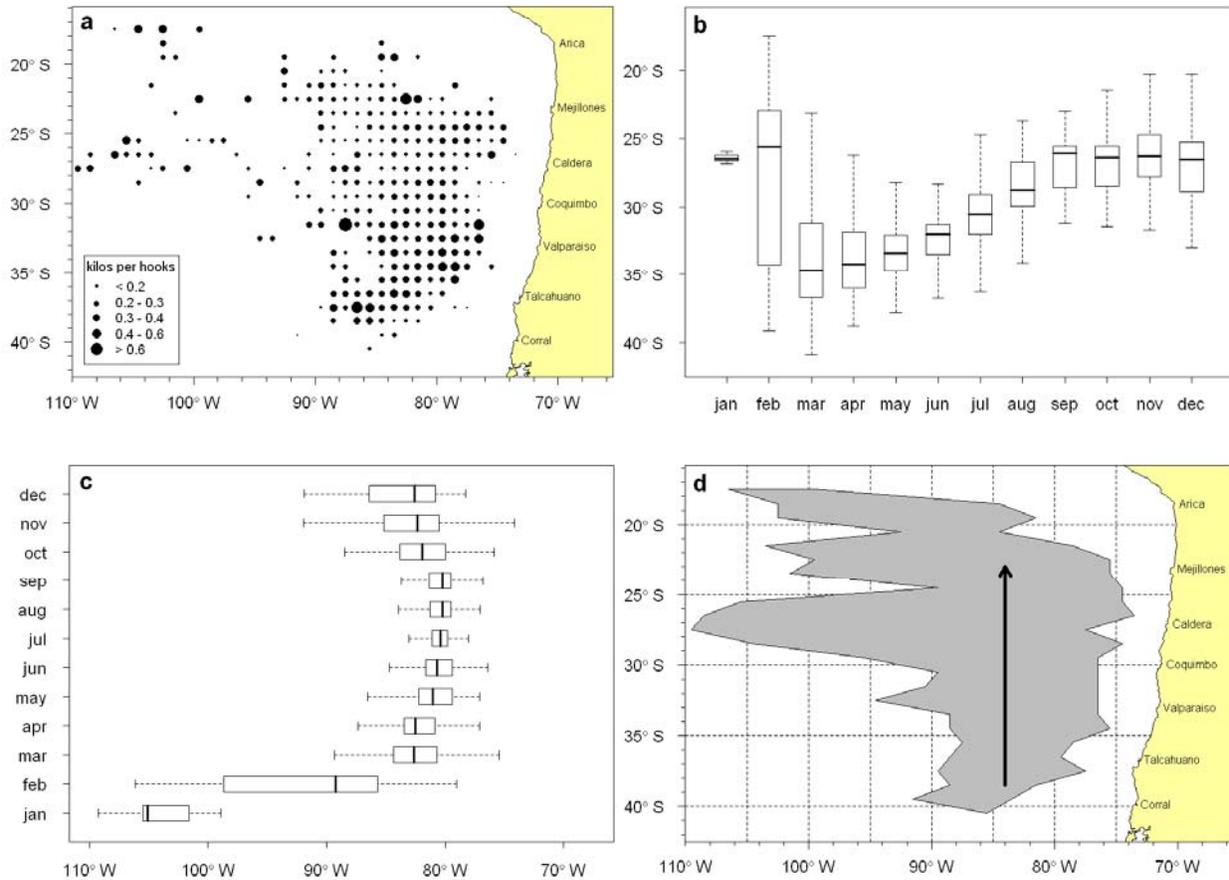


Figure 1. a) Spatial distribution of nominal CPUE for the Chilean based swordfish (*Xiphias gladius*) longline fishery from 2001 to 2005, b) boxplot of the latitudinal and c) longitudinal component of the geographic location of the swordfish longline sets. The center lines in the boxes indicates the average, and the limits of the boxes indicates the lower and upper quartiles. The vertical lines emerging from the boxes represents the 1.5 interquartile range, d) polygon that defines the spatial distribution of the fleet operation and the arrow indicates the displacement that occurs from March to September.

Figura 1. a) Distribución espacial de la CPUE nominal de pez espada (*Xiphias gladius*) durante el período 2001-2005, b) distribución de la componente latitudinal, y c) componente longitudinal de la posición geográfica de los lances de pesca de pez espada. La línea central en las cajas indica la media y los límites de las cajas indican los cuartiles inferior y superior. Las líneas verticales que salen de las cajas representan 1,5 veces el rango intercuartílico, d) polígono que define la distribución espacial de la flota, la flecha indica el desplazamiento que ocurre de marzo a septiembre.

deviance whereas the longline type explained another 2%.

Although the last variable did not generate much reduction in the residual deviance and the statistical significance values were low (Table 1), we used the statistical Akaike Information Criterion (AIC) to show that all the explanatory variables used in the GAM presented lower values than the AIC observed for the null model (Table 2). Another way to evaluate the significance of an explanatory variable in the model is by visualizing the effect that this has on the nominal CPUE. If an explanatory variable is insignificant, then a horizontal line can be drawn through the 95% confi-

dence band and the relative magnitudes of the effect of the explanatory variables are judged by the relative y-axis ranges of the spline function.

The effect of the variable latitude on the nominal CPUE is indicated in Figure 3a with the spline smoothing function and its 95% confidence bands. For swordfish, the CPUE increased with latitude from 26° to 38° S. North of 26° S and south of 38° S, the effect of the variable was not very clear because the data density was very low, producing a wide range in the standard errors. The relative magnitude of the effect of the latitude presented a range of 0.6 (-0.3 to 0.3) in the spline smoothing function on the y-axis. This range

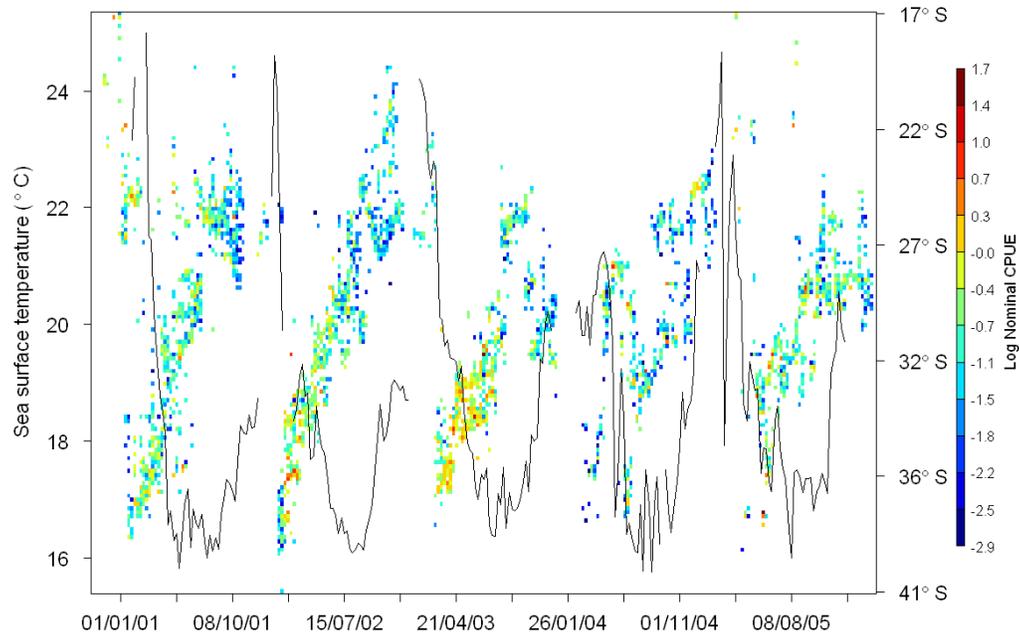


Figure 2. Nominal swordfish CPUE in relation to the time (weeks) and the geographic location (10 nm in latitude) (color dots), and the SST measure at the beginning of the fishing sets (continuous line), for the Chilean based swordfish longline fishery that operated in the southeastern Pacific ocean between January 2001 and December 2005.

Figura 2. CPUE nominal de pez espada en relación al tiempo (semanas) y la ubicación geográfica (10 mn de latitud) (puntos de color), y la TSM medida al inicio del calado de cada lance de pesca (línea continua), para la flota palangrera industrial chilena que operó en el océano Pacífico suroriental entre enero de 2001 y diciembre de 2005.

Table 1. Analysis of deviance degrees of freedom, statistic test F and its significance for the seven factors adjusted in the GAM.

Tabla 1. Análisis de devianza, grados de libertad, prueba estadística F y su significancia asociada para las siete variables explicativas ajustadas en el MAG.

Explanatory variable	Residual d.f.	Residual deviance	Deviance	d.f.	F	P	Pseudo r^2
Mean	7672	3373.3					0.0000
Latitude	7668	3064.8	308.5	4.00	211.5	0.00	0.0915
Date	7664	2990.8	74.1	3.99	50.8	0.00	0.1134
Length	7660	2915.9	74.9	3.99	51.3	0.00	0.1356
SST	7656	2876.9	38.9	3.99	26.7	0.00	0.1472
Longitude	7652	2836.4	40.5	4.00	27.8	0.00	0.1592
Lunar index	7648	2798.1	38.3	3.99	26.2	0.00	0.1705
Type longline	7647	2788.5	9.6	1.00	26.3	0.00	0.1734

considered a difference in the value of the CPUE of 35 g of swordfish per hook (Fig. 3a). The nominal CPUE increased with the variable date, from the beginning of the period analyzed until June 2003; after this, a nega-

tive effect was observed, until reaching a minimum in June 2004. Towards the end of the analyzed period, the CPUE increased again, showing a biannual signal in the effect. The relative magnitude presented a range

of 0.3 (-0.1 to 0.2) of the smoothing function; this range considered a difference of 18 g per hook (Fig. 3b). In the case of the variable length of boat, the CPUE increased until reaching a maximum at 18 m; later, a decreasing tendency was observed until 27 m, after which the increase was linear until 42 m. The relative magnitude of the effect presented a range of 0.8 (-0.6 to 0.2) in the smoothing function; this range considered a difference of 39 g per hook (Fig. 3c).

The effect of the SST on the fishery performance is noteworthy since this is the variable that presented the greatest range in the values of the spline function (≈ 1.0) (Fig. 3d). The CPUE increased nearly linearly with the SST; at 18°C, a change was seen in the rate of increase in the spline function. The effect of the SST over 23°C and below 15°C was not very clear because the data density was low, producing a wide range in the standard errors (Fig. 3d). The relative magnitude of the effect of the SST varied from -0.5 to 0.5 in the smoothing function; this range considered a difference of 60 g per hook. The nominal CPUE increased as the longitude decreased, until reaching a maximum at 77°W (Fig. 3e). For values over 87°W and below 77°W, the effect of the variable longitude was diffuse because of low data density (Fig. 3e). The relative magnitude of the effect of the variable presented a range of 0.6 (-0.4 to 0.2) in the smoothing function; this range considered a difference of 32 g per hook. The lunar index variable probably affected the vulnerability of the fish to the fishing operation; the effect of this variable was relatively small, with a range in the spline smoothing function of ≈ 0.25 , being the next-to-last variable input into the GAM (Fig. 3f). The CPUE increased as the lunar phase moved from a new to a full moon (growing phase), reaching its maximum value in the fourth quarter. The relative magnitude of the effect of the variable presented a range of -0.15 to 0.1 for the smoothing function; this range considered a difference of 14 g per hook. Finally, the nominal CPUE was greater for the American-type longline. The relative magnitude of the effect of the longline type presented a range of 0.15 (-0.15 to 0.0) based on the smoothing, a range that considered a difference of 8 g per hook in the CPUE (Fig. 3g). In the figure, the width of the horizontal line represents the number of data from each category. In this case, the American category of the variable longline type grouped 91% of the records.

Autocorrelation analysis (AA) and Fourier spectral analysis (FSA)

The time series of the nominal swordfish yields showed a marked annual cycle, with maximum values

from March to July/August of each year and then decreased during the course of the year. On the other hand, the time series of the latitudinal component of the geographic position of the set reached its southernmost location at 39°S in March, to later move progressively northwards to 17°S in February of the following year (Fig. 4a). The auto-correlation analysis applied to the time series mentioned showed a drop in the correlation at successive time intervals. For the nominal CPUE, the average autocorrelation of the series was 0.16 and the autocorrelation crossed this average level at different lags of 35, 36, 50, 51, 53, 54, 55, 59, 61, 62, 85, 86, 87, and 89 days. The autocorrelation of the series disappeared totally as of day 106 (Fig. 4b). For the average latitude, the average autocorrelation was 0.22, and the autocorrelation crossed this level with a 50-day lag. The autocorrelation of the series disappeared totally as of day 92 (Fig. 4c). A low-frequency oscillation with 30-40 day periods over the average level was observed in the function of the autocorrelation for the nominal CPUE and of 50 days in the latitudinal component of the geographic position of the set. In general, both time series showed a similar pattern on temporal scales of 90 to 110 days, respectively.

The spectral density analysis showed a variance value of 13.41 at frequencies of 0.0026 cycles per day (384 days) for the time series of the nominal catch rates (Fig. 5a). This value corresponded clearly to a source of variability on the annual scale, but other significant values of spectral density were observed to be 1.70, 1.73, and 2.05 at frequencies of 0.017, 0.026, and 0.035 cycles per day. These values corresponded to sources of low frequency variability with respective values of 59.1, 38.4, and 28.4 days, that is a strong signal on the intraseasonal scale. For the time series of the latitudinal component of the geographic position of the set, we observed a single significant variance value of 1,308 at frequencies of 0.0026 cycles per day (Fig. 5b); this value corresponded to a source of variability on the annual scale (384 days).

The results of the analysis of squared coherence between the series of the nominal catch rates and the latitudinal component of the geographic position of the set revealed two peak values (Fig. 5c). The first value of variance observed was 0.79 and the second was 0.86; these corresponded to frequencies of 0.0039 and 0.0638 cycles per day, with a phase of 160 and 151 degrees, respectively (Fig. 5d). This means that, on the annual scale, there was a strong common signal for both series, with a high squared coherence (Fig. 5c). This results show that high CPUE follow low latitude and low CPUE follow high latitude. At the frequencies greater than 0.07 cycles per day, a squared

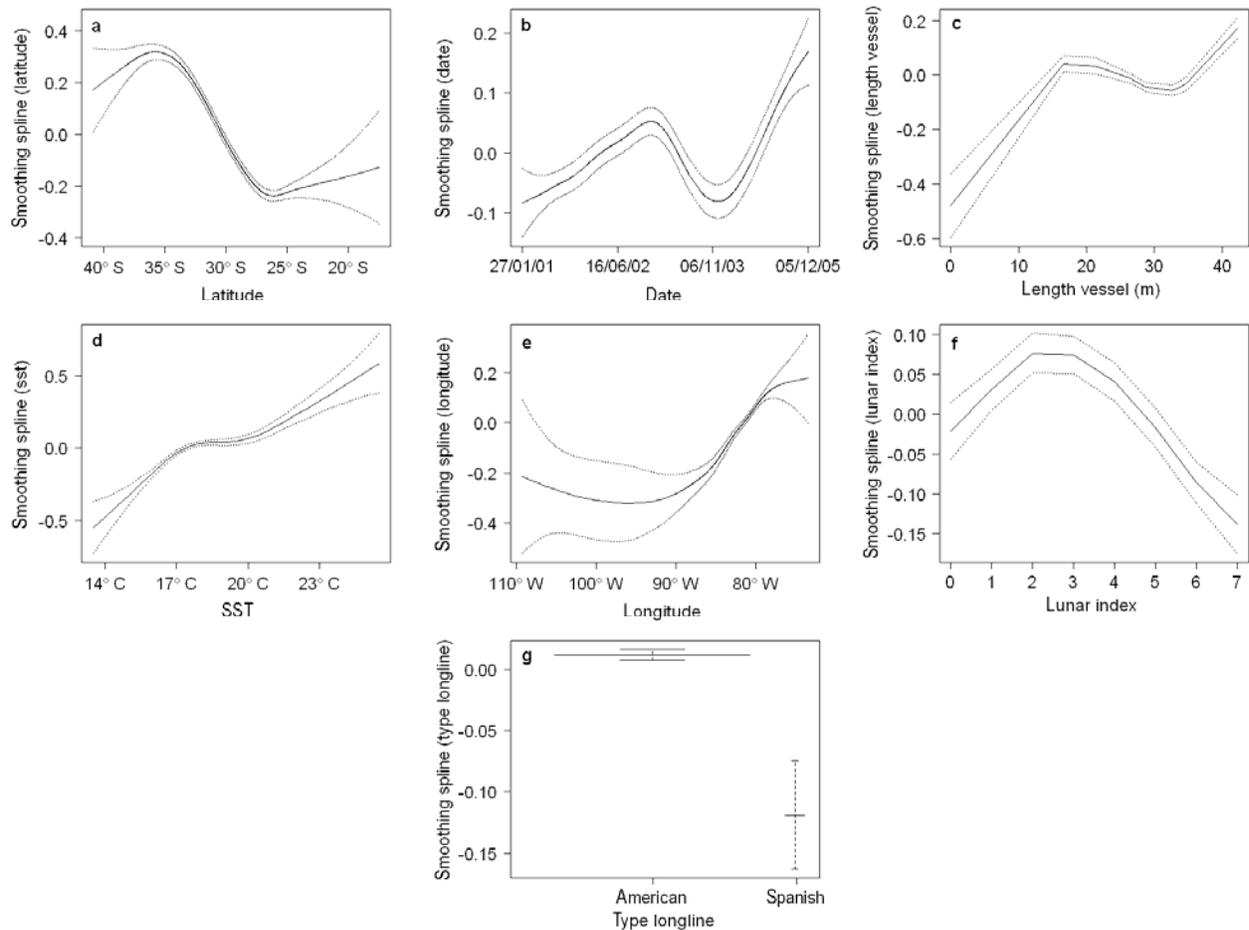


Figure 3. Effects of variables a) latitude ($^{\circ}$), b) date (day), c) length of the vessel (m), d) SST ($^{\circ}$ C), e) longitude ($^{\circ}$), f) lunar index, and g) longline type, arising from the adjustment of the generalized additive model of the swordfish nominal CPUE. The dotted lines indicate the 95% confidence bands.

Figura 3. Efectos de las variables a) latitud ($^{\circ}$), b) fecha (días), c) tamaño del barco (m), d) TSM ($^{\circ}$ C), e) longitud ($^{\circ}$), f) fase lunar, y g) tipo de palangre, derivadas del ajuste del modelo aditivo generalizado de la CPUE nominal de pez espada. Las líneas punteadas indican los intervalos de confianza del 95%.

coherence of 0.76 with a phase of 22 degrees was observed; that is a strong signal on the intraseasonal scale. Nonetheless, for these frequency bands exceeding 0.04 cycles per day, the individual spectral density analyses for both time series showed low values that were outside of the estimated 95% confidence band (Figs. 5a and 5b).

DISCUSSION

The latitudinal movement of the operation of the industrial longline fleet described in this study was also observed in the central Equatorial Pacific by Bigelow *et al.* (1999), indicating that the distribution of the

effort varied seasonally in response to the SST and the variations of energy in the frontal zone of the SST, with the maximum CPUE in the cold periods in spring and a minimum in the warm periods in winter, reflecting the annual cycles of variability that are observed for the SST and the CPUE.

The results obtained with respect to the variations in the latitudinal component of the geographic position of the fishing sets also agreed with the results found for the north Pacific. The nominal yields presented a marked annual spatial-temporal pattern, with high nominal CPUE values in autumn/winter and from 38° to 32° S, and an SST oscillating from 17 to 19° C. Later, the nominal CPUEs fell sharply, moving north

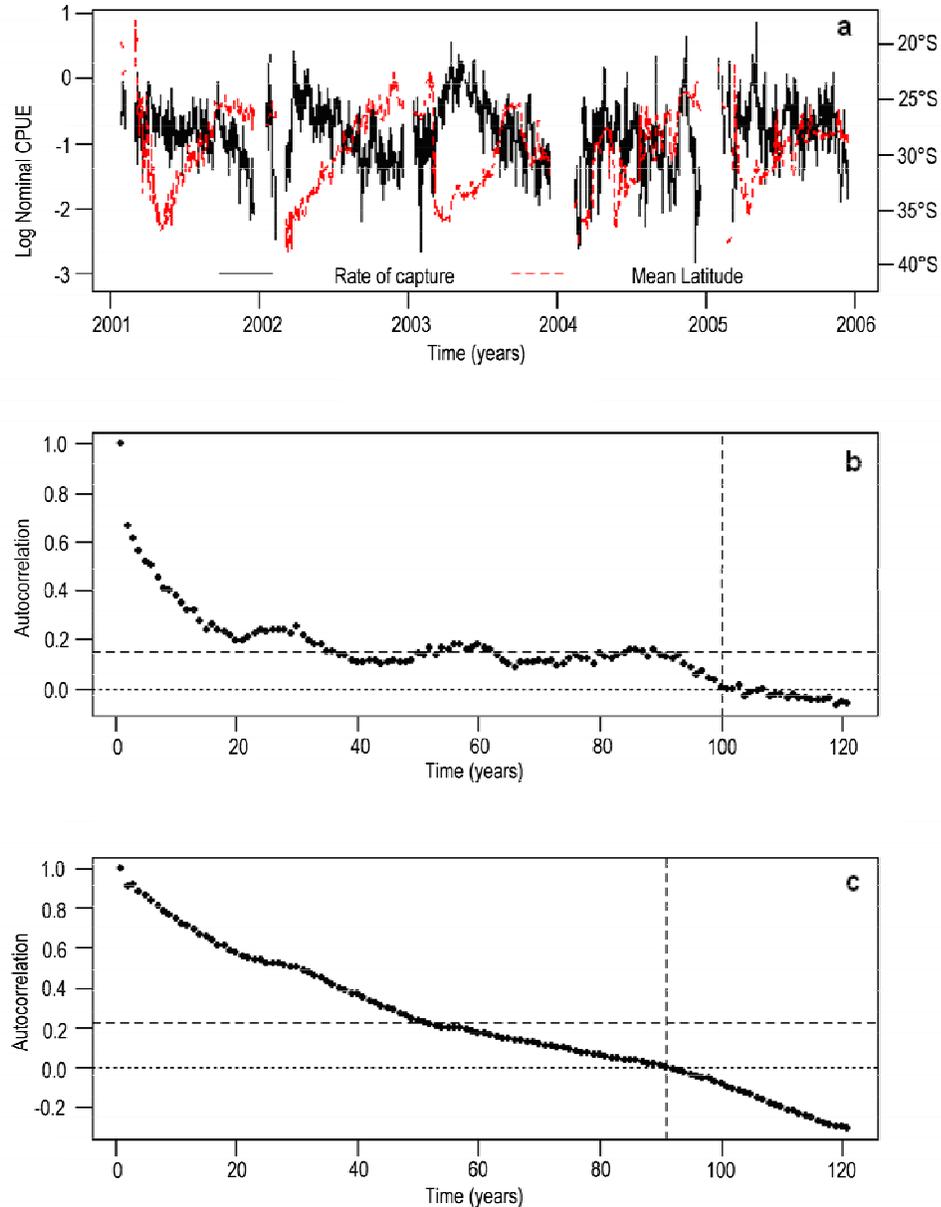


Figure 4. a) Time series of nominal CPUE (logarithm) and the latitudinal component of the geographic position of the swordfish longline set, b) autocorrelation function of the nominal CPUE, and c) autocorrelation function of the latitudinal component of the nominal CPUE. The horizontal segmented line in b) and c) represents the average level of autocorrelation and the vertical line represents the point where the autocorrelation function crosses the zero level (dotted line).

Figura 4. a) Serie temporal de la CPUE nominal (logaritmo) y del componente latitudinal de la posición geográfica del lance de pesca de pez espada, b) función de autocorrelación de la CPUE nominal, y c) función de autocorrelación de la componente latitudinal de la CPUE nominal. La línea segmentada horizontal en b) y c) representa el nivel medio de autocorrelación y la vertical representa el punto donde la función de autocorrelación cruza el nivel cero (línea punteada).

of 32°S in spring/summer (Fig. 2). This geographic distribution pattern in the fishing yields varied seasonally in response to the annual cycle in the movements of certain isotherms of SST and the variations in frontal energy in the southeastern Pacific.

Using the historical catches of the Japanese longline tuna fishery in the central North Pacific, Sosa-Nishizaki & Shimizu (1991) described strong variability in the nominal CPUE on a broad spatial-temporal scale, similar to that observed for the

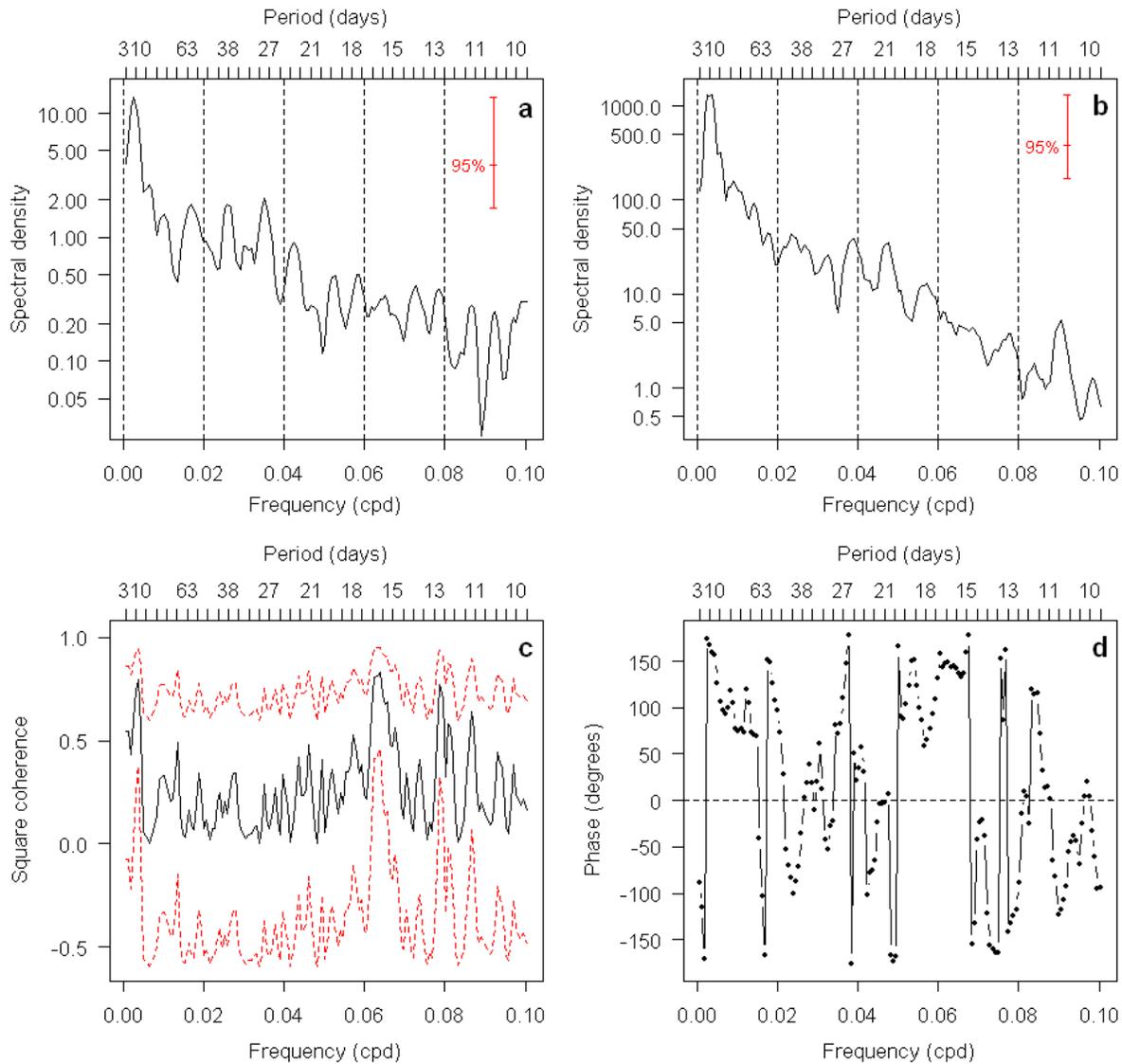


Figure 5. a) Spectral density of the swordfish nominal CPUE, b) spectral density of the latitudinal component of the geographic position of the longline sets and confidence bands of 95%, c) square coherence between time series and 95% confidence band, and d) phase between the time series in degrees.

Figura 5. a) Densidad espectral de la CPUE nominal de pez espada, b) densidad espectral de la componente latitudinal de la posición geográfica del lance de pesca de pez espada y sus intervalos de confianza del 95%, c) coherencia cuadrada entre las series temporales e intervalos de confianza del 95%, y d) fase entre las series temporales en grados.

longline swordfish fishery off Hawaii. Bigelow *et al.* (1999) reported that high CPUEs occurred over a range of SST from 15 to 20°C, in the presence of strong frontal energies, similar to that observed in this study for the longline fishery that operates in the southeastern Pacific ocean. In the present work, we did not evaluate the effect of the frontal energy of the SST, although in the north Pacific it is mentioned that the mechanisms that associate the increased swordfish

fishery performance with high frontal energy values of SST may not be related to the preference for certain gradients in the SST but rather to the increment of food at the fronts due to the higher lateral and vertical mixing that favors primary and secondary production (Olson & Buckus, 1985). The main prey in the swordfish diet reported for the southeastern Pacific are from the groups Cephalopoda and Teleostei (Barbieri *et al.*, 1998; Donoso *et al.*, 2003), with teleost fishes being

Table 2. Results of the GAM adjusted to the catch rate of swordfish, in terms of the deviance, degree of freedom and the AIC criterion.

Tabla 2. Resultados del MAG ajustado a las tasas de captura del pez espada, en términos de la devianza, los grados de libertad y el criterio AIC.

Explanatory variable	d.f.	Deviance	AIC
Mean		2788.5	14062.5
Latitude	1	3292.7	15335.6
Date	1	3031.2	14700.8
Length	1	3038.3	14718.7
SST	1	3106.4	14888.8
Longitude	1	3086.3	14838.9
Lunar index	1	3045.5	14736.8
Type longline	1	3047.6	14742.1

the main food item in autumn and winter, when high CPUE values are observed between 38° and 32°S. From September on, the most important prey are the cephalopods, with low CPUE values, mainly north of 32°S. This pattern has also been observed in the northeastern Atlantic ocean, where swordfish feed on pelagic species in more coastal waters and prey mainly on squid in oceanic waters (Hernández-García, 1995).

The interannual fluctuations of variance described for the SST, as recorded on each boat at the beginning of the fishing set, were greatest on the annual scale (Fig. 5), with latitudinal movements that go from 39° S in autumn to 20° S in spring-summer, that is, with maximum temperatures (> 24°C) in spring-summer and minimum temperatures (\approx 16°C) in autumn-winter, describing a seasonal cycle of heating and expansion. This oceanographic process involves moving masses of subtropical oceanic water (> 18.5°C and salinity > 34.9), with equatorial-subtropical origins and a zonal orientation, manifesting the seasonal cycle of solar heating and the change in the transport of the ocean's main surface water masses (Blanco *et al.*, 2001). Most of these energy fluctuations have been observed in coastal series off South America in the interannual frequency band, associated with El Niño-Southern Oscillation (ENSO) events (Shaffer *et al.*, 1999; Pizarro *et al.*, 2002). This interannual pattern of oceanographic variables suggests that low nominal CPUEs were present in the oceanic waters in spring-summer, whereas the high nominal CPUEs were recorded in more coastal waters in autumn-winter, probably due to the reduced area occupied by the 16 to 20°C isotherms in this period (Bigelow *et al.*, 1999). It

should be noted that this interannual variability linked to the equatorial dynamic could constitute a potential predictive tool for the performance of the swordfish fishery off the Chilean coast. The results presented in this work support the hypothesis that the spatial-temporal swordfish distribution could respond to spatial-temporal movements of certain SST isotherms.

The low frequency fluctuations observed in the nominal yields with periods of 28, 38, and 59 days (Figs. 4 and 5) could correspond to a biological response to the energy fluctuations observed in the South American coastal series in the intraseasonal band, likely due to the poleward propagations of coastal trapped waves, forced by the eastward propagation of Kelvin equatorial waves (Huyer *et al.*, 1991; Shaffer *et al.*, 1997; Hormazábal *et al.*, 2001). This variability appears to be forced remotely from the Equatorial Pacific by Madden-Julian oscillations in the intraseasonal band (Shaffer *et al.*, 1997; Hormazábal *et al.*, 2002) and by equatorial winds in the seasonal band (Pizarro *et al.*, 2002). According to Hormazábal *et al.* (2004), the coastal trapped waves could destabilize the surface circulation of the ocean, generating coastal jets or meander currents that begin to become instable and give rise to the formation of mesoscale eddies. The activity of the mesoscale eddies in the coastal transition zone off Chile (Hormazábal *et al.*, 2004) experiences strong interannual variability in kinetic energy, which is modulated by the El Niño/La Niña cycle, with an annual signal having maximum energy values in May-June south of 30°S and minimum values in spring-summer north of 30°S. These oceanographic data, plus those found in this study (elevated CPUE values from March to July-August south of 32°S, followed by decreased yields north of 32°S), allow us to recommend continuing the analysis of this type of information in order to formulate hypotheses with respect to this zone of the southeastern Pacific, since the performance of the industrial longline swordfish fishery is also associated with the presence of mesoscale phenomena, which provide an appropriate environment for increased food concentrations. Thus, the swordfish gather around these structures for purposes of feeding, thereby increasing their availability and vulnerability, and consequently the nominal catch rates of the longline fleet.

From a global perspective, the GAM analysis was limited in that the ocean structure was inferred based strictly on SST estimates, and did not consider other variables that could be included in the model. For example, data on salinity could improve the explanatory ability of the model since they produce better estimates of the frontal energy in terms of the differences in the thermohaline structure between the water

masses (Bigelow *et al.*, 1999). Data on the sea surface height, measured by remote sensors, reflect changes in the caloric content of the water column; for example, a depression (elevation) in the sea surface height indicates a rising (deepening) of the isotherm. The mechanisms associated with the increased nominal CPUE may not be associated with the caloric content of the water column, since the swordfish can perform daily vertical migrations through water masses with differences beyond 19°C (Carey & Robinson, 1981), but rather may be associated with the concentration of food due to changes in the position of the isotherm in the water column.

The lunar phase affects swordfish vulnerability since their depth distribution could be altered in response to the percentage of light, probably due to the importance of their vision for feeding (Carey & Robinson, 1981). The nominal CPUE increased during the periods prior to full moon events due to an increase in swordfish vulnerability because these events improve their acute vision or modify their behavior, favoring increased vertical movements (Bigelow *et al.*, 1999). On the other hand, the fishing yield increased along with the length of the industrial boats because the larger vessels have a greater hold capacity and a greater fishing capacity in terms of autonomy and quantity of hooks per set.

Although the available data series covers only five years, it is possible to state that, during the period analyzed, two peak yields were observed: one in autumn-winter 2003 and the other in 2005. This nearly biannual behavior observed in the effect of the temporal variable on the model could be related to one of the main sources of variability (2-3 years) observed in the oceanographic data of coastal stations along South America (Blanco, 2006). This source of variability, nearly biannual, could be explained by the delayed oscillator model (White *et al.*, 2003), in which Rossby waves are propagated towards the west taking ≈ 6 , ≈ 12 , and ≈ 36 months to reach the western coasts near $\approx 7^\circ\text{N}$, $\approx 12^\circ\text{N}$, and $\approx 18^\circ\text{N}$ on, respectively, biannual, interannual, and decadal temporal scales. These are reflected as coupled equatorial waves that propagate slowly towards the east, co-varying with the SST, the depth of the 18°C isotherm, and the zonal anomalies of the surface wind, taking ≈ 6 , ≈ 12 , and ≈ 36 months to reach the central and eastern equatorial ocean. These coupled equatorial waves produce a delayed negative feedback in the negative SST anomalies.

Finally, the results obtained clearly identified a spatial-temporal pattern in the performance of the industrial longline swordfish fishery operating in the eastern Pacific ocean, with movements from 41° to

17°S from March to December (Figs. 1b and 4a), through a narrow longitudinal band (Fig. 1c). This analysis shows that the main sources of variability in the nominal fishing yields occurred in two main frequency bands: interannual (384 days) and intraseasonal (28, 38, 59 days). On the other hand, although only 17% of the variance in the nominal swordfish catch rates was explained by the GAM, the explanatory level of the model could be improved by incorporating additional variables such as data from remote sensors (temperature, chlorophyll-a, sea level anomaly, etc.), climatological data (salinity) from general oceanic circulation model outputs, or estimates of primary productivity or prey species abundance. Moreover, to demonstrate the effect of the frontal energy of the SST on swordfish availability, high-resolution satellite data (Pathfinder) could be used on spatial and temporal scales appropriate for the swordfish aggregations, occupying an algorithm for the detection of borders used to identify fronts in the high resolution SST satellite images (AVHRR), as was done for the swordfish study in the northeastern Atlantic ocean (Podestá *et al.*, 1993).

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