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Research Article

Environmental conditions associated with swordfish size compositions and catches off the Chilean coast

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ABSTRACT. Multivariate analyses were applied to explore the relative influence of environmental factors on swordfish (*Xiphias gladius*) size compositions and catches off Chile. A first analysis was applied to a commercial fishing data base made up of biological-fishery and environmental records from 343 fishing sets performed between 2000 and 2002 by two longline vessels. Furthermore, a data base of fishing research cruises over the Cordillera de Nazca was analyzed; this set consisted of biological-fishery and environmental satellite information recorded for 43 fishing sets done in summer and winter 2003 and autumn and spring 2005. Principal component and hierarchical classification analyses were applied to seven environmental variables (Latitude, Longitude, Sea surface temperature, Chlorophyll *a* concentration, Sea surface height, Sea surface salinity, Bathymetry), all of which may affect the distribution of swordfish size compositions and catches. The analyses indicate four spatial groups representing specific latitudinal locations and typologies of environmental conditions associated with the swordfish size compositions and catches in the study area. Swordfish were caught within a range of SST that varied from 16 to 22ºC, with larger catches given smaller SSTs, greater chlorophyll concentrations, and higher latitudes. A latitudinal gradient in size composition is affirmed, with juvenile specimens associated with warmer conditions, greater salinity, lower chlorophyll concentrations, and lower latitudes. The geographic distribution of the recruitment zone is associated with the Cordillera de Nazca marine area.

Keywords: environmental conditions, swordfish, multivariate analysis, Chile.

Condiciones ambientales asociadas a la estructura de tallas y capturas de pez espada frente a Chile

RESUMEN. Se aplicaron análisis multivariados para explorar la influencia relativa de factores ambientales sobre la estructura de tallas y capturas de pez espada (*Xiphias gladius*) frente a Chile. Un primer análisis se aplicó a una base de datos de pesca comercial, correspondiente a registros biológico-pesqueros y ambientales de 343 lances de pesca efectuados por dos embarcaciones palangreras entre el 2000 y 2002. Además, se analizó una base de datos de cruceros de pesca efectuados en la zona de Cordillera de Nazca, que correspondió a información biológico-pesquera y ambiental satelital registrada en 43 lances de pesca, efectuados en verano e invierno de 2003, y otoño y primavera de 2005. Se aplicaron análisis de componentes principales y análisis de clasificación jerárquica a siete variables ambientales (Latitud, Longitud, Temperatura superficial del mar, Concentración de clorofila *a*, Altura superficial del mar, Salinidad superficial del mar y Batimetría), todas las cuales podrían afectar la distribución de la estructura de tallas y capturas de pez espada. Los resultados obtenidos, indicaron la presencia de cuatro agrupaciones espaciales que representan una localización latitudinal específica y una tipología de las condiciones ambientales, asociadas a la estructura de tallas y capturas de pez espada. Al respecto, los ejemplares de pez espada fueron capturados en un rango de TSM que varió entre 16º y 22ºC, las mayores capturas se obtuvieron a menores TSM, mayores concentraciones de clorofila y mayores latitudes. Se afirma la existencia de un gradiente latitudinal en la estructura de tallas, donde la presencia de ejemplares juveniles se asocia a condiciones más cálidas del ambiente, mayor salinidad, menor clorofila y menores latitudes. Se señala además, que la distribución geográfica de la zona de reclutamiento de pez espada, está asociada al área marina de la Cordillera de Nazca.

Palabras clave: condiciones ambientales, pez espada, análisis multivariado, Chile.

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INTRODUCTION

The effects of the environment (temperature, salinity, chlorophyll concentration, turbidity, marine currents and prey abundance) affect the success of the catches and the distribution of highly migratory marine resources such as swordfish (*Xiphias gladius*) and tuna (Scombridae) (Draganik & Cholyst, 1988; González, 1993; Podesta *et al*., 1993; Yáñez *et al*., 1996; Bigelow *et al*., 1999; Nieto, 1999; Sedberry & Loefer, 2001; Seki *et al*., 2002). These factors are important and should be considered in the modeling of these fisheries (Yáñez *et al*., 2003, 2007).

Off Chile, the environmental conditions are dominated by the Chile-Peru Current System, a highly productive marine ecosystem due to nutrient transport by large-scale horizontal advection and persistent coastal upwelling (Bernal *et al*., 1983). Several important factors sustain the high biological productivity observed in this eastern boundary system. These include the Peru-Chile Undercurrent, which transports nutrient-rich, oxygen-poor waters southward, and persistent coastal upwelling that is generated by the action of the predominant winds and results mainly in rising nutrient-rich waters towards the surface. This favors high phytoplankton production, which is then available for zooplankton and fishes.

Swordfish are caught off Chile from its northern limit to around 40ºS, associated with waters with surface temperatures between 13° and 24ºC. The national longline fleet operates mainly between 21.5º and 39ºS, and between 120 and 600 nm from the coast (Donoso & Cerna, 1999). The swordfish distribution depends on the specimen's age or size and sex, and varies seasonally. Juveniles are more abundant in tropical and subtropical waters, migrating to higher latitudes when they mature. The larvae are found associated with waters with temperatures over 24ºC (Matsumoto & Kazama, 1974). The adults concentrate in areas where their prey are abundant, commonly along frontal zones, where the oceanic currents or water masses intercept, creating turbulence and marked surface temperature and salinity gradients (Sakagawa, 1989).

The objective of this study is to analyze the environmental conditions associated with swordfish size compositions and catches off Chile, considering the hypothesis that "different climatic phenomena affect the oceanic environment off Chile and the distribution of swordfish sizes and catches".

MATERIALS AND METHODS

The study area is located off the coast of Chile and divided into two areas. The first area is where two representative vessels of the Chilean longline fleet operated from 2000 to 2002 (24º-36ºS and 78º-85ºW) (Fig. 1). The second area was a marine sector of the Cordillera de Nazca (21º-26ºS and 80º-85ºW), where fishing cruises were carried out on board fishing vessels.

Commercial fishery data base

The data base analyzed corresponded to the biological-fishery and environmental records of 343 fishing sets carried out by two longline vessels that operated between 2000 and 2002 in the fishing area mentioned earlier (Fig. 1). The following reference and biological-fishery information was recorded per fishing set: date and hour of longline setting and retrieval, latitude (LAT), longitude (LON), swordfish lower jaw fork length (LJFL), and catch in weight (CIW); on average, this data referred to 1320 hooks per set, with a standard deviation of 25.

The environmental satellite information in the data base corresponded to weekly images generated according to the daily averages of the following variables: Sea Surface Temperature (SST), Chlorophyll *a* concentration (Chl-a), Sea Surface Height (SSH), Sea Surface Salinity (SSS), and Bathymetry (BAT) (Fig. 2). A Geographic Information System (GIS) IDRISI32 (Clark University ©, Clark Labs, Worcester, MA, USA) was applied, allowing us to extract the environmental satellite data associated with the fishing sets, that is, SST, Chl-a, SSH, SSS, and BAT (Fig. 2).

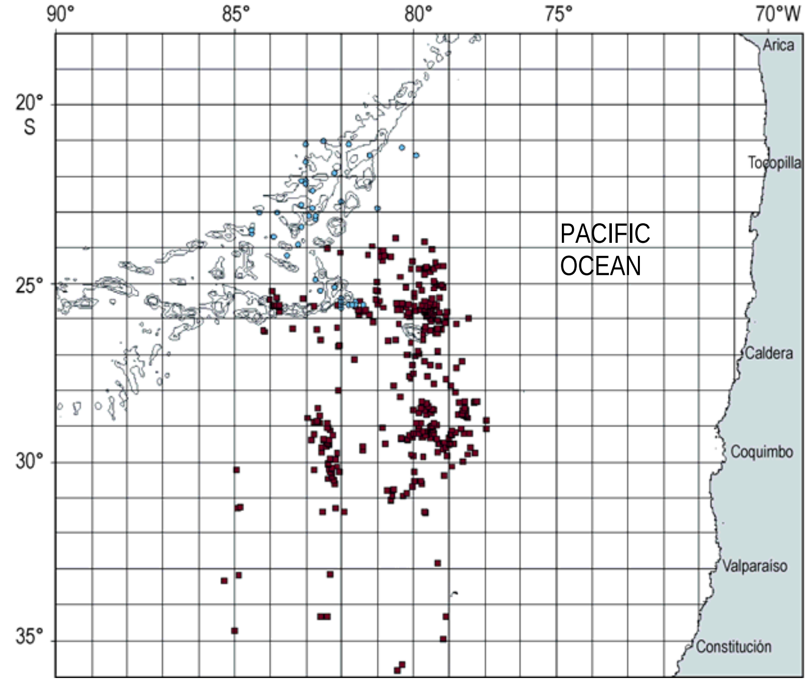

Figure 1. Study area and longline sets done by two fishing vessels from 2000 to 2002 (squares) and by seasonal research cruises in 2003 and 2005 (circles). The bathymetric profile is indicated.

Figura 1. Zona de estudio y lances de pesca efectuados por dos embarcaciones palangreras durante 2000 y 2002 (cuadrados) y por cruceros de pesca estacionales en 2003 y 2005 (círculos). Se indica además el perfil batimétrico.

The SSS was obtained from the model NCOM (Navy Coastal Ocean Model), which assimilates the data of SSH anomalies from satellite altimetry, SST, and temperature and salinity profiles obtained with a CTD (Kara *et al.*, 2006). The bathymetry was obtained from satellite altimetry (Smith & Sandwell, 1997).

Data base from fishing cruises in the Cordillera de Nazca

This data base corresponded to the biological-fishery and environmental satellite information recorded during 43 fishing sets carried out during fishing cruises in summer and winter 2003 (Yáñez *et al.*, 2004) and autumn and spring 2005 (Yáñez *et al.*, 2006) in the oceanic area associated with Cordillera de Nazca (Fig. 1). The operating protocol followed was the same as that used by the commercial fishing vessels. The reference and biological-fishery information registered per set corresponded to the date, season of the year, time of longline setting and retrieval, LAT, LON, LJFL, and CIW. The data base covered the following environmental satellite variables: SST, Chl-a, SSH, SSS, and BAT (Fig. 2).

Statistical analysis

Associations between environmental variables and swordfish size compositions and catches off Chile were done using exploratory analysis methods for multivariate data (Escofier & Pages, 1990; Jobson, 1992a, 1992b; Lebart *et al.*, 1995) and SPAD software (CISIA-CERESTA©, Montreuil, France). To identify the main associations between the variables responsible for the total variability of the data analyzed, a Principal Component Analysis (PCA) was applied in which the environmental variables (SST, Chl-a, SSS, SSH, BAT) were considered to be active and the reference (LAT, LON) and biological-fishery (LJFL, CIW) variables to be descriptive. Although we only present the results relative to the two first components, the others were also analyzed. A Hierarchical Classification Analysis (HCA) was applied to the first 10 principal components in order to identify homogenous sets of observations. Characterization through the environmental variables was done by dividing the data into two clusters or groups. For this characterization, we selected the most important environmental variables for each group or cluster according to the result of a non-parametric hypothesis test, comparing the

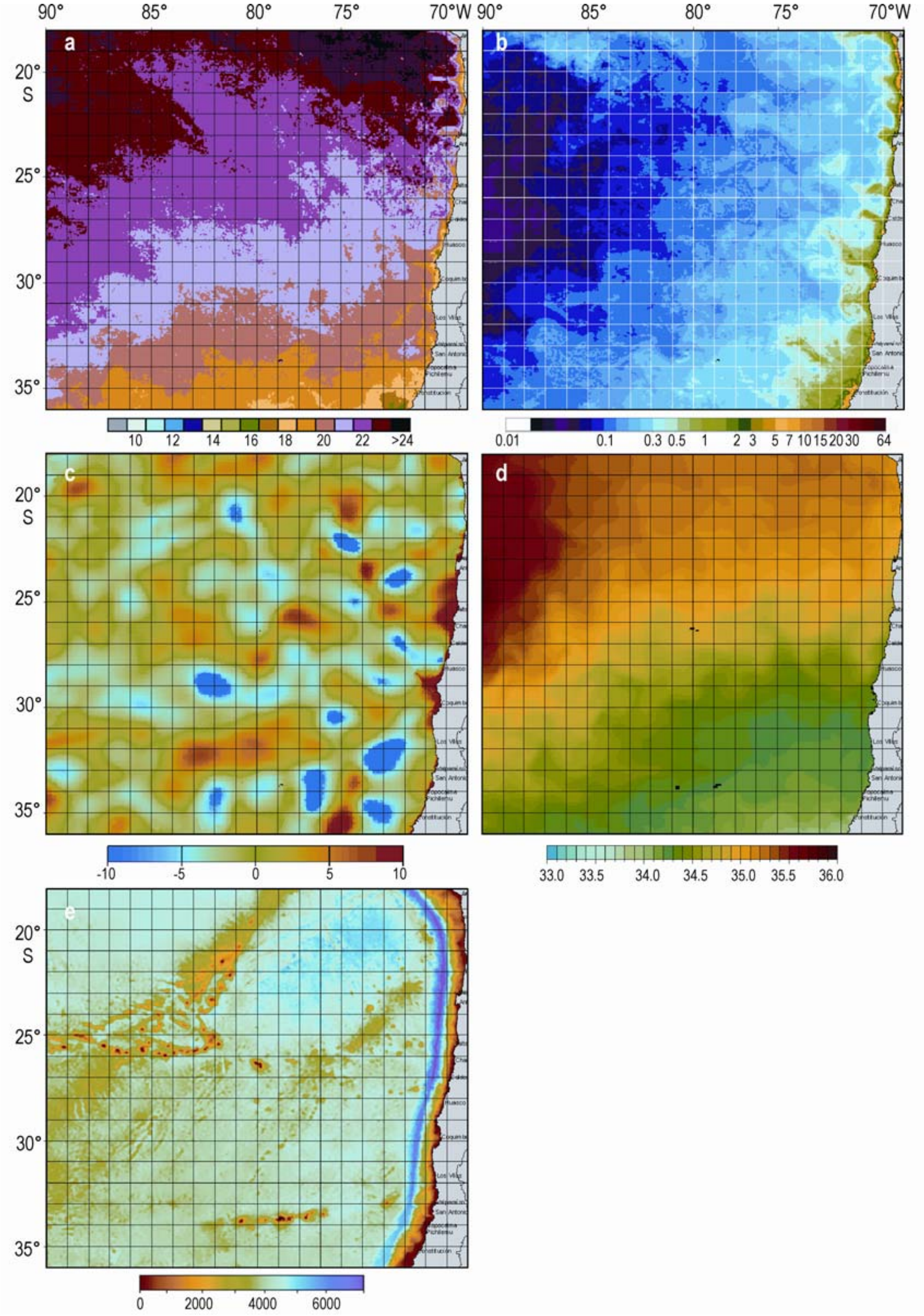

Figure 2. Example of environmental satellite information used: a) sea surface temperature, b) chlorophyll *a*, c) sea surface height, d) sea surface salinity, and e) bathtymetry.

Figura 2. Ejemplo de la información satelital ambiental utilizada: a) temperatura superficial del mar, b) clorofila-a, c) altura superficial del mar, d) salinidad superficial del mar y e) batimetría.

average of each environmental variable in the cluster to the average of the total sample (Jobson, 1992a, 1992b; Lebart *et al*., 1995).

RESULTS

Environment–resource relationships in the commercial fishery

The PCA done for the 343 commercial fishing sets indicates that the two first axes explain 69% of the variance of the data, with the first component contributing 49% (Table 1).

Table 1. Eigenvalues and percentage of explanation of the main axes (Commercial fishery data).

Tabla 1. Valores propios y porcentaje de explicación de los ejes principales (Datos de pesca commercial).

Axis	Eigenvalues	Explained percentage	Accumulated percentage
1	2.44	49	49
2	0.99	20	69
3	0.79	16	84
4	0.47	9	94
5	0.31	6	100

The first axis was highly correlated with the active variables SST (0.83), SSS (0.81), and Chl-a (-0.82) and the descriptive variable LAT (-0.77). The second axis was highly correlated with SSH (0.71), BAT (0.53), and the descriptive variable LON (-0.59) (Table 2).

The results of the HCA indicated the existence of two large groups or clusters that contain 60 and 40% of the data (classes 1 and 2, respectively). The characteristic values of the classes by the continuous active and descriptive variables are presented in Table 3. The results obtained in the characterization of the pelagic environment with the commercial fishing data base indicated the presence of a latitudinal gradient in the environmental variables SST, Chl-a, and salinity. The characterization of the groups obtained from the HCA showed the presence of a first zone (class 1) associated with greater Chl-a values (0.15 mg m^{-3}), lower SST (16.8ºC), lower salinity (34.4), and greater LJFL of swordfish (206 cm), and located at higher latitudes (28.6ºS). The other zone (class 2) was associated with low Chl-a values (0.09 mg m^{-3}), higher SST (18.2ºC), greater salinity (34.7), and individuals with lower LJFL (193 cm), and was found at lower latitudes (26ºS).

Table 2. Correlation of active and descriptive variables in the three main axes.

Tabla 2. Correlación de las variables activas e ilustrativas en los tres primeros ejes principales.

Active variables	Axis 1	Axis 2	Axis 3
SST	0.83	-0.33	-0.07
Chl-a	-0.82	0.30	-0.03
SSH	0.43	0.71	-0.55
SSS	0.81	-0.04	-0.08
BAT	0.48	0.53	0.69
Descriptive variables	Axis 1	Axis 2	Axis 3
LAT	-0.77	-0.03	-0.11
LON	0.18	-0.59	-0.09
LJFL	-0.27	0.1	0.02
CIW	-0.28	0.16	0

Environment–resource relationships during seasonal cruises

The PCA for the 43 fishing sets from seasonal cruises (summer, autumn, winter, spring) carried out around Cordillera de Nazca indicated that the first factorial axis explained 39% of the variance, whereas the second axis explained 28%. Together, these two axes grouped 67% of the total variability (Table 4).

The first axis was highly correlated with the active variables SST (-0.89) and SSS (-0.85), and the descriptive variable LAT (0.82). The second axis was correlated mainly with the active variables Chl-a (0.78) and BAT (-0.82) (Table 5).

In the HCA, two groups were distinguished by highly differentiated observations. The characteristic values of the classes per variables are presented in Table 6. Class 1 was associated with greater SST values (20.8ºC), lower Chl-a (0.08 mg m^{-3}), higher SSS (35.2), lower SSH (0.9 cm), lower swordfish LJFL (165 cm), and catches at lower latitudes (22.7ºS). Class 2 was characterized by lower SST values (18.4ºC), greater Chl-a (0.1 mg m^{-3}), lower salinity (34.9), greater SSH (6.3 cm), greater swordfish LJFL (177 cm), and catches at higher latitudes (24.8ºS).

Pelagic ecosystem associated with swordfish

When integrating and spacializing the results obtained with the multivariate analysis into the GIS, four groups were observed, presenting a typology of the

Table 3. Continuous variables that significantly define the obtained HCA classes, considering a cut of the tree in two, based on commercial fishing data of 2000-2002. SD: standard deviation.

Tabla 3. Variables continuas que definen significativamente las clases obtenidas del HCA, considerando un corte del árbol en dos, según los datos de pesca comercial 2000-2002. SD: desviación estándar.

		LAT	LON	LJFL	CIW	SST	Chl-a	SSH	SSS	BAT
Class 1	Mean	28.6	80.0	206	574	16.8	0.15	0.2	34.4	3943
	SD	1.4	1.3	17	339	0.7	0.03	2.3	0.1	115
Class 2	Mean	26.0	80.4	193	437	18.2	0.09	2.1	34.7	4094
	SD	1.0	1.3	20	295	0.5	0.03	2.3	0.1	189
General	Mean	27.3	80.2	199	506	17.5	0.12	1.2	34.6	4018
	SD	1.8	1.3	20	325	0.9	0.04	2.5	0.2	174

environmental conditions associated with swordfish size compositions and catches in the study area (Figs. 3 and 4).

Spatial variability can be observed in the size compositions and catches, which present a marked latitudinal gradient with lower swordfish LJFL and catches towards the north (Fig. 4). To the south, the LJFL and catches are greater. This latitudinal gradient in size compositions and catches is associated with a specific environmental condition. In fact, the lower LJFL and catches of swordfish are associated with greater SST, greater SSS, and lower Chl-a (Fig. 4). However, the greater length and catches are associated with lower SST, lower SSS, and greater Chl-a values (Fig. 4).

DISCUSSION

Catches and the environment

The influence of the environmental factors on the swordfish distribution has been the object of diverse studies (Podestá *et al.* 1993; Yáñez *et al.*, 1996; Bigelow *et al.*, 1999; Nieto, 1999; Yáñez *et al.*, 2004, 2006). While the most studied variable has been SST, Podestá *et al.* (1993) explored the relationship between thermal fronts at the ocean surface and the swordfish catch rates in the fishery of the western North Atlantic, using satellite SST to analyze three physical variables: horizontal thermal gradient, distance to the nearest thermal front, and front density. Most of the fishing effort is done along thermal fronts, but the highest catch rates are not clearly explained by the nearness to these. Bigelow *et al.* (1999) analyzed the swordfish catch rates in the North Pacific with additive generalized models, finding a relationship with SST, the thermal gradient, and seasonal variations in the thermal and frontal habitat. The results show that the best catch yields occur in waters with an SST between 14° and 16ºC around the thermal fronts located between 35° and 40ºN. Both studies concluded that these fish concentrate along thermal fronts in response to the aggregations of prey found there more than because of a determined SST.

In the southeastern Pacific, the use of satellite SST began in the Chilean fishery fleet with the SATAL project (Barbieri *et al*., 1987, 1990, 1991). Based on this project, an important biological-fishery and environmental (SST, thermal gradients) data base was generated that allowed the development of diverse scientific works (González, 1993; Yáñez *et al.*, 1996; Nieto, 1999). According to Yáñez *et al.* (1996), swordfish are caught between 14° and 20ºC off Chile, with optimal temperatures that vary seasonally, Nieto (1999) constructed a model of likely fishing zones for the artisanal fishery in central Chile using satellite SST images and thermal gradients. Moreover, she concludes that the swordfish distribution in the study area is related to the SST that varies from 19ºC in March (summer) to 13ºC in August (winter); the greatest catches per unit effort (CPUE) were recorded at SSTs between 15 and 17ºC.

The dominant marine currents constitute another important environmental factor affecting the availability of food for swordfish. Studies indicate that the horizontal distribution of these resources is associated with the presence of mesoscale structures (oceanic upwelling or eddies, current fronts, depression zones) (Brill *et al.*, 1993; Polovina *et al.*, 1999; Seki *et al.*, 2002). The presence of these structures is visualized in the satellite images of SSH and geostrophic currents. The SSH is an indicator of what occurs below the sea surface; for example, how the thermocline moves up and down. When the SSH is positive (above normal), the thermocline is deeper and produces gyres or

Table 4. Eigenvalues and degree of explanation of the main axes (Seasonal cruises data).

Tabla 4. Valores propios y porcentaje de explicación de ejes principales (Datos de cruceros estacionales).

Axis	Eigenvalues	Explained percentage	Accumulated percentage
1	1.98	39	39
2	1.36	28	67
3	0.72	14	81
4	0.69	13	94
5	0.25	6	100

Table 5. Correlation with the factorial axes of active and descriptive variables.

Tabla 5. Correlación con los ejes factoriales de las variables activas e ilustrativas.

Active variables	Axis 1	Axis 2	Axis 3
SST	-0.89	-0.20	-0.18
Chl-a	0.23	0.78	0.05
SSH	0.64	-0.22	-0.73
SSS	-0.85	0.22	-0.34
BAT	0.04	0.82	-0.2
Descriptive variables	**Axis 1**	**Axis 2**	**Axis 3**
LAT	0.82	-0.28	0.18
LON	-0.31	-0.30	-0.36
LJFL	0.30	0.08	0.00
CIW	0.18	-0.36	-0.08

Table 6. Average value of active and descriptive variables by class obtained in the hierarchic classification analysis, based on research cruise data from summer, autumn, winter, and spring. SD: standard deviation.

Tabla 6. Valor medio de variables activas e ilustrativas por clase obtenidas del análisis de clasificación jerárquica, de acuerdo a los datos de los cruceros de verano, otoño, invierno y primavera. SD: desviación estándar.

		LAT	LON	LJFL	CIW	SST	Chl-a	SSH	SSS	BAT
Class 1	Mean	22.7	82.8	165	370	20.8	0.08	0.9	35.2	3221
	SD	1.2	1.2	18	257	0.8	0.02	4.9	0.2	733
Class 2	Mean	24.8	82.0	177	411	18.4	0.1	6.3	34.9	2890
	SD	1.2	0.5	9	212	0.8	0.02	1.8	0.1	901
General	Mean	23.6	82.5	172	389	19.8	0.09	3.2	35.1	3083
	SD	1.6	1.0	15	236	1.4	0.02	4.7	0.2	814

anticyclonic currents (Seki *et al.*, 2002). On the contrary, when the SSH is negative (below normal), the thermocline is nearer the surface, allowing the development of cyclonic gyres. Therefore, the SSH is very useful for knowing whether the thermocline is shallower or deeper than normal. The thermocline is an important vertical boundary where diverse fish species concentrate.

Recent studies relate the movements of tuna and swordfish, as measured with ultrasound telemetry, to Chl-a and satellite turbidity, showing that these species remain within a narrow range of said parameters (Brill & Lutcavage, 2001), unlike SSTs, which is tolerated in wide ranges. This conclusion is supported by the location of the bluefin tuna school recorded during aerial prospecting trips carried out in 1997 (Lutcavage, 1998). Brill & Lutcavage (2001) concluded that the SST and its gradients themselves are not necessarily good predictors of the movements or aggregations of tuna and swordfish because they are imperceptible to these fish, which routinely withstand vertical temperature gradients of strong magnitudes. Nonetheless, the SST gradients can be predictors of movements and abundance of tuna and swordfish, according to that observed by Fiedler & Bernard (1987) and Bigelow *et al.* (1999), if these reflect an increase in prey abundance.

The results obtained indicate that, for the study area and period, the swordfish specimens were caught in an SST range that varied between 16° and 22ºC, with the greatest catches occurring at the lowest SST, greatest Chl-a, and highest latitudes. Therefore, the

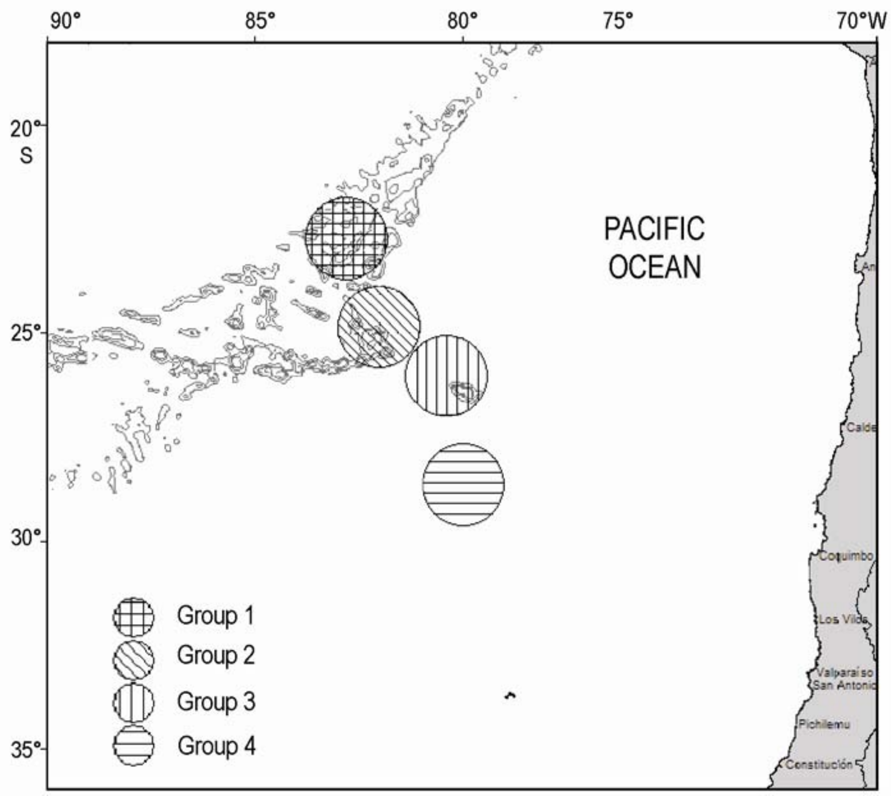

Figure 3. Spatial groups of environmental characteristics associated with swordfish catches and size compositions.

Figura 3. Grupos espaciales de características ambientales asociadas a la estructura de tallas y capturas de pez espada.

greatest catches are associated, more than with a determined SST range, with the presence of an area of growing productivity (thermal front, upwelling) and relatively high prey abundances (Podestá *et al.*, 1993; Olson *et al.*, 1994; Bigelow *et al.*, 1999). This conclusion is also supported by recent studies on bigeye tuna (Bertrand *et al.*, 2002) and swordfish (Sedberry & Loefer, 2001), which indicate that the vertical and horizontal distributions of these predators depend more on the distribution of the prey than on the physical and chemical parameters, since these fish have the physiological capacity to follow their prey where the abiotic conditions can not be optimum for the predators (Brill & Lutcavage, 2001). Thus, the relationship between the swordfish distribution and abiotic parameters (SST, SSS, Chl-a concentration) is indirect; the swordfish follow the prey such that the distribution of the former can be related to oceanographic characteristics. In fact, although thermal fronts are rich in food (prey), the total alone is insufficient for explaining the distribution and catchability of these fishes. Swartzman *et al*. (1999) and Bertrand *et al*. (2002) indicate that, along with the number of prey, their distribution type (aggregated or not) is a key parameter. Although abundant, disperse prey availability favors catchability, aggregated prey attracts predators but their catchability decreases as the bait on the hooks must compete with the prey. It thus seems pertinent to focus on their distribution in function of the availability of food. Swordfish feed on pelagic and mesopelagic organisms (mainly mollusks, fish and crustaceans) from 1 to 142 cm in length (Blackburn, 1968; Sund *et al.*, 1981; Chancollon *et al*., 2006).

Catch size composition and the environment

Spatial and temporal variability was observed in the swordfish catch size composition (DeMartini *et al.*, 2000), revealing a greater percentage of large fish (males > 156 cm, females > 172 cm) caught north of 35°N, in colder waters at the end of summer and beginning of winter. On the other hand, relatively larger numbers of “small-sized” swordfish (females < 126 cm; males < 118 cm) were caught south of 22ºN, in warmer waters located near the Equator. These observations are consistent with several hypotheses of energy migrations and heat conservation in body mus-

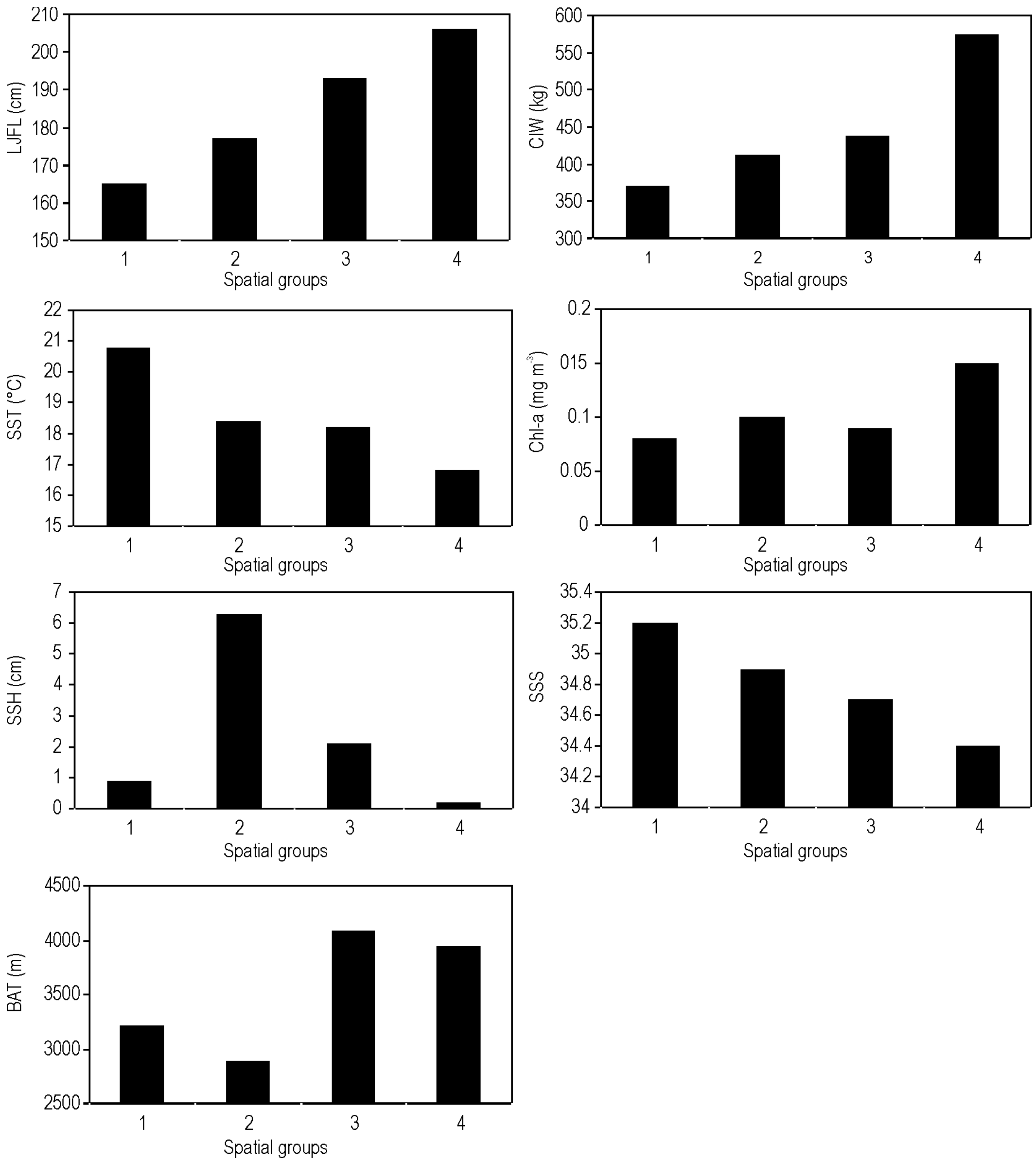

Figure 4. Biological-fishery and environmental characteristics associated with four spatial groups.

Figura 4. Características biológico-pesqueras y ambientales asociadas a los cuatro grupos espaciales.

cles. Latitude has also been observed to have a strong influence on size composition but not on longitude (DeMartini *et al.*, 2000).

Mejuto & García (1998) found that the SST around the fishing area of the Spanish longline fleet in the southeastern Pacific fluctuated between 16° and 21ºC, with peak CPUE values between 19° and 21ºC, verifying the relationship between temperature and average catch weight. The highest average weights were obtained between 16° and 18ºC, whereas the lowest average weights were 60 kg, obtained at 19° and 21ºC.

Our results indicate the existence of a latitudinal gradient in swordfish size composition in which the presence of juvenile specimens is associated with warmer environmental conditions, higher salinity, and lower Chl-a. Moreover, we found that the geographic distribution of the swordfish recruitment zone is associated with Cordillera de Nazca zone and has been described as north of 24°S (Yáñez *et al.*, 2004). Finally, if understanding the effects of the physical environment on the behavior of highly migratory fish like tuna (Scombridae) and billfishes (Istiophoridae and

Xiphiidae) is critical to robust population evaluations (Brill & Lutcavage, 2001), the influences of the environment on the distribution of fishery resources constitute important factors that should be included in the management models.

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