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Research Article

Coupling between the environment and the pelagic resources exploited off northern Chile: ecosystem indicators and a conceptual model

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ABSTRACT. The eastern boundary of the Chile-Peru Current System constitutes one of the most biologically productive ecosystems in the world, due largely to coastal upwelling and the horizontal advection of nutrients. In this ecosystem, El Niño events are of great importance in the interannual variability of the environment. A change was observed in the environmental regime at the beginning of the 1970s with the onset of the 1972-1973 El Niño, marking an important decrease in the anchovy fishery (*Engraulis ringens*). After the mid-1970s, sardine (*Sardinops sagax*) landings increased noticeably. A second regime shift at the end of the 1980s was seen mostly in the noticeable recovery of anchovy and the decline of sardine. Herein, we present an integrated conceptual model of the different local and large-scale phenomena that affect the marine environment off northern Chile and the distribution and abundance of pelagic resources. The model considers an analysis of environmental and bio-fishery data on different scales and describes how the interdecadal (associated with regime shifts) and interannual (associated with El Niño events) fluctuations in the Equatorial Pacific are manifested in the eastern South Pacific and, therefore, in the northern zone off Chile, affecting the annual cycle, the dynamic of the coastal trapped waves, and coastal upwelling. In this framework, interdecadal fluctuations play an important role in the anchovy-sardine-anchovy replacement sequence.

Keywords: pelagic fishery, environmental variability, conceptual model, northern Chile.

Acoplamiento entre el ambiente y los recursos pelágicos explotados en el norte de Chile: un modelo conceptual

RESUMEN. El borde oriental del Sistema de Corrientes de Chile-Perú constituye uno de los ecosistemas de mayor productividad biológica del mundo, debido principalmente a la surgencia costera y advección horizontal de nutrientes. En este ecosistema, los eventos El Niño son de mayor importancia en la variabilidad interanual del ambiente. No obstante, un cambio de régimen ambiental es observado a inicio de los 70's el que hubiera comenzado con El Niño 1972-73 y que marca la gran disminución de la pesquería de anchoveta (*Engraulis ringens*); en tanto, desde mediados de los 70's los desembarques de sardina (*Sardinops sagax*) aumentan notablemente. Un segundo cambio de régimen se observa a finales de los 80's, representado principalmente por la notable recuperación de anchovy y disminución de sardina. Se presenta un modelo conceptual integrador de los diferentes fenómenos locales y de gran escala que afectan el ambiente marino del norte de Chile, y la distribución y abundancia de recursos pelágicos. El modelo considera análisis de datos ambientales y bio-pesqueros a distintas escalas, y describe como las fluctuaciones interdecadales (asociadas a cambios de régimen) e interanuales (asociadas a los eventos El Niño) del Pacífico Ecuatorial se manifiestan en el Pacífico Sur Oriental y por tanto en la zona norte de Chile, afectando el ciclo anual, la dinámica de las ondas atrapadas a la costa y la surgencia costera. En este marco, las fluctuaciones interdecadales estarían jugando un rol importante en la secuencia del reemplazo anchoveta-sardina-anchoveta.

Palabras clave: pesquerías pelágicas, variabilidad ambiental, modelo conceptual, norte de Chile.

INTRODUCTION

The eastern boundary of the Chile-Peru Current System is a highly productive marine ecosystem due to the transport of nutrients by large-scale horizontal advection and persistent coastal upwelling (Bernal *et al.*, 1983). Hence, Peru and Chile have become primary fishery countries world-wide. In Chile, annual landings fluctuate around 5 million tons; 90% of these are made up by the combined pelagic resources, with the landings from northern Chile constituting 42% (SERNAPESCA, 1957-2004). In this area, the fishery is based successively on anchovy (*Engraulis ringens*) and sardine (*Sardinops sagax*), with noticeable changes related to fishing effort and environmental fluctuations (Yáñez *et al.*, 2001).

Ocean-climate changes have been related to alterations in the marine ecosystems on several spatial-temporal scales (Alheit & Bernal, 1993; Hare *et al.*, 2000; Chavez *et al.*, 2003; Yáñez *et al.*, 2003; Alheit & Niquen, 2004). Physical forcing is obvious on the seasonal scale, with variations in temperature and coastal upwelling, for example, controlling productivity, growth, and migration. On an interannual scale, this forcing is associated with El Niño-La Niña events; that is, when the tropical ecosystems are directly affected, the eastern boundary of the Pacific is remotely forced by the concomitant oceanic-atmospheric teleconnections (Shaffer *et al.*, 1999; Pizarro *et al.*, 2002). A high degree of uncertainty exists regarding the mechanisms involved in the interdecadal changes (Bakun & Broad, 2001).

The oceanographic variables that most influence the fishery resources seem to be temperature, mixing layer depth (MLD), thermocline depth, upwelling intensity, and the surface current fields (Bakun & Broad, 2001). Since many physical processes cause changes in the sea surface temperature (SST), such anomalies may be symptomatic rather than causal. The MLD, the nutricline, and the depth of the photic zone can influence primary production, affecting the availability of nutrients and the intensity of the light to which the autotrophic species are exposed. Long-term changes in the boundaries of the thermocline depth can directly influence habitats, change the characteristics of mesoscale eddies and filament formation, and affect upwelling.

Observations of currents over the continental slope off Chile have revealed a complex structure of variability in the intraseasonal, seasonal, and interannual bands (Shaffer *et al.*, 1999). This variability is remotely forced in the equatorial Pacific by Madden-Julian oscillations in the intraseasonal band (Shaffer *et*

al., 1997; Hormazábal *et al.*, 2002), equatorial winds in the seasonal band (Pizarro *et al.*, 2002), and the El Niño-Southern Oscillation (ENSO) cycle in the interannual band (Shaffer *et al.*, 1999; Pizarro *et al.*, 2002). This variability, which is connected to the equatorial dynamic, makes it possible to predict the area's oceanographic conditions months in advance.

In the Peru-Chile Current System, coastal trapped waves, Rossby waves, and mesoscale eddies and meanders have been identified as the dominant physical processes of variability (Hormazábal *et al.*, 2002, 2004; Pizarro *et al.*, 2002). These processes have diverse spatial and temporal scales. In other regions, they have been observed to be factors that contribute to the balance between the source of nutrients towards the photic layer and primary production (Chávez *et al.*, 1998; McGillicuddy *et al.*, 1998; Cipollini *et al.*, 2001; Uz *et al.*, 2001). Some theories attribute great importance to the variability of currents and mesoscale structures in the distribution and abundance of fishery resources in their different developmental stages (Sakagawa, 1989).

The oceanographic processes that affect the life-style of the species act on different spatial-temporal scales, on a continuum from hours to centuries and from centimeters to thousands of kilometers (Haury *et al.*, 1978; Levin, 1992). Perry *et al.* (2000) proposed that fish catchability can fluctuate on diverse spatial-temporal scales. These variations can reflect changes in the physical and biological environment that occur on similar scales. These authors then proposed a conceptual diagram on spatial (1 to 10,000 km) and temporal (day to century) scales, with characteristics of processes in the physical and biological marine environment and in the fishery activities.

Chávez *et al.* (2002) studied the impact of the 1997-1998 El Niño events on central California and defined a conceptual model of the associated ecosystem changes. The model describes, on an interannual scale, the relationships between resource abundance and distribution in different developmental stages and the levels of temperature, salinity, chlorophyll, sea level, and zooplankton, amongst others. Later, Chavez *et al.* (2003) studied the long-term changes in anchovy and sardine associated with important changes in the condition of the Pacific Ocean. The resulting conceptual model referred to the variability of the ecosystem proxies and to changes in the regime on a multi-decadal scale similar to that covered in the present work (1950-2002). Finally, Bertrand *et al.* (2004) proposed an integrated context of factors that, occurring on different spatial-temporal scales, could be used to interpret the effect of an El Niño event on the pe-

lagic fish populations. Those temporal scales ranged from days to decades and the spatial scales from local to oceanic.

The ecosystem in question is affected by ENSO events (Philander, 1990) and El Niño long-term environmental changes (Cañón, 1986; Hare & Mantua, 2000; Chávez *et al.*, 2003). El Niño events cause horizontal and vertical migration in the fishery resources and the more intense events also affect reproduction and survival (Sharp & McLain, 1993; Tarazona & Castillo, 1999; Bakun & Broad, 2001), generating strong socio-economic impacts (Glantz, 1998). However, this phenomenon is connected to large-scale environmental changes, making it difficult to isolate its effect on the resources and to evaluate how the related biological processes interact with exploitation, causing short-term disturbances and fishery collapses (Myers *et al.*, 1995; Hutching, 2000; Yáñez *et al.*, 2003). Under these circumstances, the fishery regulations face serious difficulties (Bernal, 1990; Bakun & Broad, 2001; Sepúlveda *et al.*, 2003).

Thus, the objective of the present study is to analyze the fluctuations of the environment and the pelagic resources off northern Chile, and to propose an integrated conceptual model of these.

MATERIALS AND METHODS

Analyzed information

Data on the landings (1950–2004) come from Chilean (SERNAPESCA, 1950–2004) and Peruvian (www.imarpe.gob.pe) fishery logbooks. Both data bases report on seiners and refer to fishing days and days with catch off northern Chile (1963–2002). They also consider biomass and recruitment of anchovy (1984–2002) and sardine (1974–2002) and estimates of anchovy eggs and larvae (1993–2002) off northern Chile. These fisheries have been subjected to bans on extraction during reproductive and recruitment periods since 1983 (Table 1).

Monthly averages (1950–2002) of the following variables, recorded at coastal stations in the study area, were also analyzed: SST, average sea level (ASL), air temperature (AT), and wind direction and magnitude for estimating Ekman transport (ET; Bakun *et al.*, 1974) and the turbulence index (TI; Elsberry & Garwood, 1978). The monthly averages of the Southern Oscillation Index (SOI; Allan *et al.*, 1991) and SST in El Niño regions 1+2 and 3.4 (web NOAA-NCEP) were also considered. The depth of the base of the thermocline (Zb) was also used; this was located on a 5° x 2° (longitude x latitude) grid and centered on 24°S and 72.5°W; the Zb was calculated with expand-

able and mechanical bathythermographic data (Pizarro & Montecinos, 2004).

Data collected during research cruises (financed by the Fondo de Investigación Pesquera) carried out between 1993 and 2002 were analyzed for the vertical distribution (0–200 m) of temperature (T), salinity (S‰), oxygen (O), and chlorophyll-*a* (CLOA), available from the Servicio Hidrográfico y Oceanográfico (SHOA) of the Chilean Navy, along with SST data from NOAA satellites (1987–2002) and CLOA data from SeaStar and Terra & Aqua satellites (1997–2002).

Data treatment

The anchovy and sardine resources were analyzed through landings, fishing effort, and the catch per unit effort (CPUE) abundance index (Espíndola *et al.*, 2005). Moreover, we considered estimates of abundance and recruitment for virtual population analyses (VPA), hydro acoustic analyses (sA), and the egg production method (EPM). The relationship between CPUE and biomass was analyzed according to Harley *et al.* (2001), such that the coefficient of catchability (*q*) can vary with abundance, resource behavior, fishing strategy, and the environment.

Fluctuations in the catch and CPUE were analyzed with the CLIMPROD system, which consider standard fishing effort and environmental variables to be explanatory (Fréon *et al.*, 1993). In order to isolate the most important modes in the variability of the oceanographic and fishery series, we used both standard empirical orthogonal functions (EOF) (Tanco & Berri, 2000) and complex EOF analyses (Horel, 1984). With the latter, it is possible to determine the relationships of the phases between the variables and, as with the standard EOF, reconstruct the series based on the modes.

We used the environment-resource interactions and bibliographic information to develop an integrated conceptual model that sustains the working hypothesis on different spatial-temporal scales. For example, on the interannual scale, it considers the relationships between biological-fishery changes and El Niño events whereas, on the interdecadal scale, it establishes relationships between the anchovy and sardine fluctuations and large-scale environmental changes.

RESULTS

Landings and CPUE

Anchovy landings in Chile and Peru follow practically the same tendency, including the variations associated

Table 1. Anchovy and sardine closed seasons in northern Chile.**Tabla 1.** Vedas extractivas de anchoveta y sardina en la zona norte de Chile.

Year	Anchovy	Sardine	Year	Anchovy	Sardine
1983	No Closed Season	27 Aug – 13 Sep	1993	1 – 31 Jan 29 Nov – 31 Dec	1 – 27 Feb 2 Aug – 10 Sep
1985	15 Apr – 31 Dec	23 Apr – 22 May 17 – 24 Aug 9 – 22 Sep 14 – 31 Dec	1994	1 Jan – 13 Feb 18 – 31 Dec	14 Feb – 13 Mar
1986	1 – 31 Jan 1 – Jul	1 Jan – 2 Feb 12 Jul – 10 Aug	1995	1 Jan – 5 Feb 13 Feb – 5 Mar 21 Jul – 27 Aug 27 Nov – 27 Dec	21 Jul – 27 Aug
1987	No Closed Season	1 – 25 Feb 1 Aug – 10 Sep	1996	1 – 21 Aug 16 – 31 Dec	1 – 21 Aug
1988	23 Jan – 31 Mar 1 Aug – 11 Sep 19 – 31 Dec	1 Feb – 11 Mar 1 Aug – 11 Sep	1997	1 – 19 Jan 29 Jan – 16 Feb 15 Aug – 13 Sep 17 – 31 Dec	
1989	1 Jan – 19 Mar 31 Jul – 29 Sep 25 – 31 Dec	20 Jan – 28 Feb 17 Jul – 24 Sep	1998	1 Jan – 1 Feb 11 – 24 Feb 15 Jul – 16 Aug 26 Aug – 9 Sep 5 – 19 Oct 1 – 30 Nov 2 – 31 Dec	
1990	1 Jan – 19 Mar 31 Jul – 1 Sep 12 – 31 Dec	22 Jan – 4 Mar 16 Jul – 8 Sep	1999	26 Jul – 31 Aug 1 – 12 Sep	26 Jul – 12 Sep
1991	1 Jan – 10 Mar 8 – 31 Dec	No Closed Season	2001	23 Jan – 25 Feb (6 nm) 6 – 26 Aug 17 – 30 Sep	26 Jul – 8 Sep 2000
1992	1 Jan – 29 Feb 10 Aug – 17 Sep 30 Nov – 31 Dec	27 Jan – 7 Mar 17 Aug – 26 Sep	2002	5 – 19 Jan 19 Aug – 8 Sep	

Source: Subsecretaría de Pesca

with El Niño events (Fig. 1a). This fishery collapsed at the beginning of the 1970s, and was replaced by the sardine fishery off northern Chile and Peru (Fig. 1b). After 1985, however, the sardine fishery showed an important decline, first in Chile and later in Peru (Fig. 1b), at the same that the anchovy fishery recovered notably (Fig. 1a).

By examining the relationship $CPUE = q B^\beta$, in which the anchovy biomass is estimated with the

EPM, the parameter $\beta = 0.55$ indicates a bias when considering the CPUE proportional to the abundance (Fig. 2a). The estimates of the sardine CPUE seem to be more reasonable, with growth until the mid-1980s and then a clear decrease (Fig. 2b).

In order to evaluate the seasonal anchovy and sardine pattern, we excluded the period following 1984 due to the effects of the application of extraction bans (Table 1). Moreover, for anchovy, we did not consider

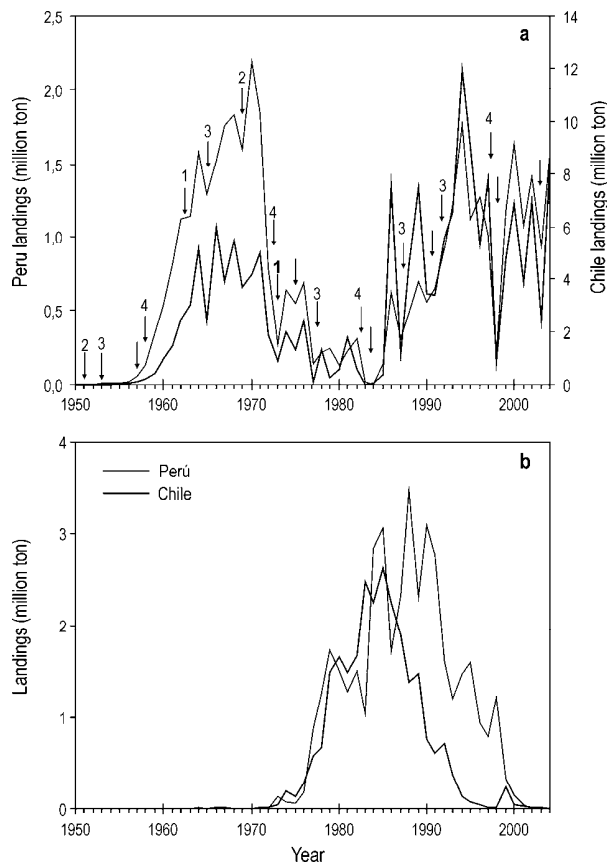


Figure 1. Annual landings of a) anchovy, and b) sardine in Peru and northern Chile (1950-2004). The arrows represent El Niño events and numbers the intensity (1 less intense and 4 more intense).

Figura 1. Desembarques anuales de a) anchoveta, y b) sardina en Perú y norte de Chile (1950-2004). Las flechas indican eventos El Niño y los números la intensidad (1 menos intensos y 4 más intensos).

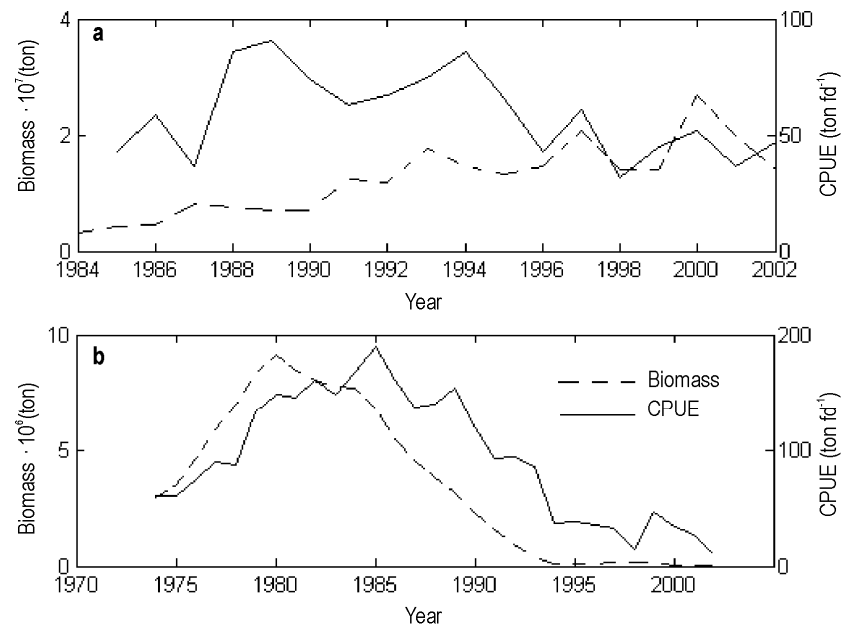


Figure 2. VPA Estimated biomass and standard CPUE for a) anchovy (1984-2002), and b) sardine (1974-2002).

Figura 2. Biomasa estimada por APV y CPUE estándar de a) anchoveta (1984-2002), y b) sardina (1974-2002).

the 1976-1984 period since the fleet was mainly targeting sardine at this time (Fig. 1). Thus, the seasonality of the CPUE and the anchovy landings increased, particularly in summer although also in winter (Fig. 3a). For sardine, the seasonal component was greater during the second semester and minimal in spring-summer, with a secondary increase in March (Fig. 3b).

Environment defined by local winds

A study of the seasonality of the meteorological variables showed that the TI was at a minimum in June and peaked from October to January (Fig. 4a). The ET cycle, however, was inverse; offshore (westward) transport was greater in spring-summer and lesser in June (Fig. 4b). The depth of the mixing layer in the coastal and oceanic sectors exhibited maximum values in winter, related with the disappearance of the seasonal spring-summer thermocline (Fig. 5).

CLIMPROD models were previously adjusted for the anchovy (1957-1977) and sardine (1973-1995) fisheries off northern Chile (Yáñez *et al.*, 2001). For anchovy, we considered a lineal-lineal model, taking into account the fishing effort and TI as variables that explained the drop in the CPUE ($r^2 = 0.91$). For sardine, we used a linear-quadratic model in which fishing effort and SST explained the increase and later decrease in the CPUE ($r^2 = 0.93$).

In the present work, we again analyzed the sardine (1973-2002) and anchovy (1984-2002) fisheries for the study area by adjusting non-conventional CLIMPROD models. The relationship between sardine landings and fishing effort were lineal-positive, increasing until peaking between 1983 and 1987 and then returning to the original values (Fig. 6a). The exponential-positive relationship between landings and the ET was greater in 1982-1987 (Fig. 6b). The sardine CPUE also showed positive, although not lineal, relationships with fishing effort and ET; the values increased from 1973 to 1985 and later decreased again (Figs. 7a and 7b). The important relationship detected between these two explanatory variables should be pointed out (Fig. 8a), as should the strong relationship between ET and turbulence (Fig. 8b).

For anchovy, the direct relationship between recruitment and biomass was noteworthy (Fig. 9a). The relationship between recruitment and ET was inverse (Fig. 9b), as was the relationship between biomass and ET (Fig. 10a) and the more disperse relationship between standard fishing effort and ET (Fig. 10b). Although not as clear as that of sardine, the relationship between anchovy landings and fishing effort was also positive (Fig. 11).

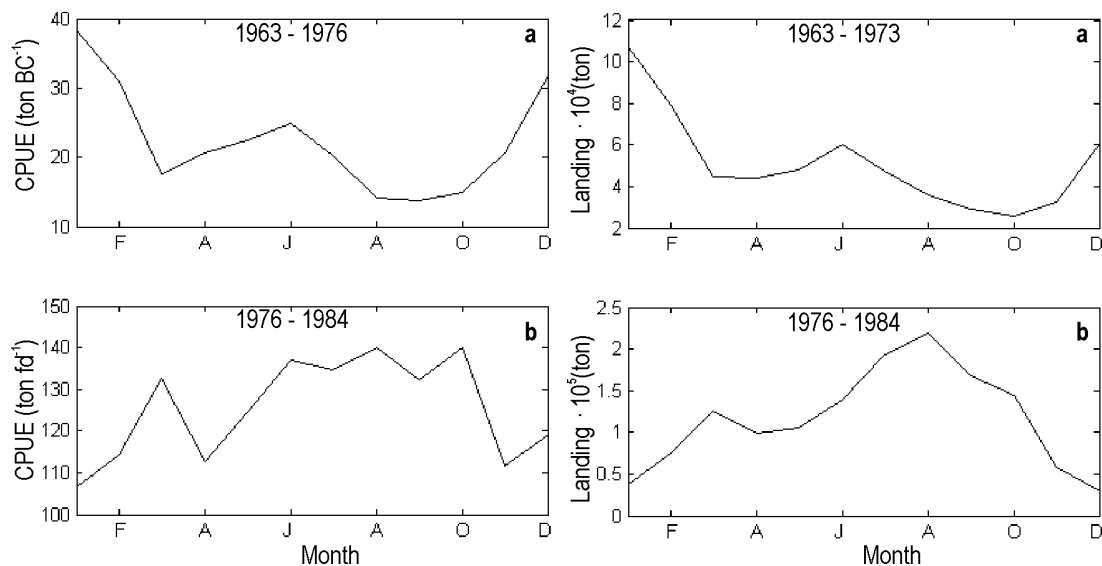


Figure 3. CPUE and landings seasonality of a) anchovy, and b) sardine. The selected periods do not include the closing periods.

Figura 3. Estacionalidad de la CPUE y del desembarque de a) anchoveta, y b) sardina. Los períodos seleccionados no consideran vedas extractivas.

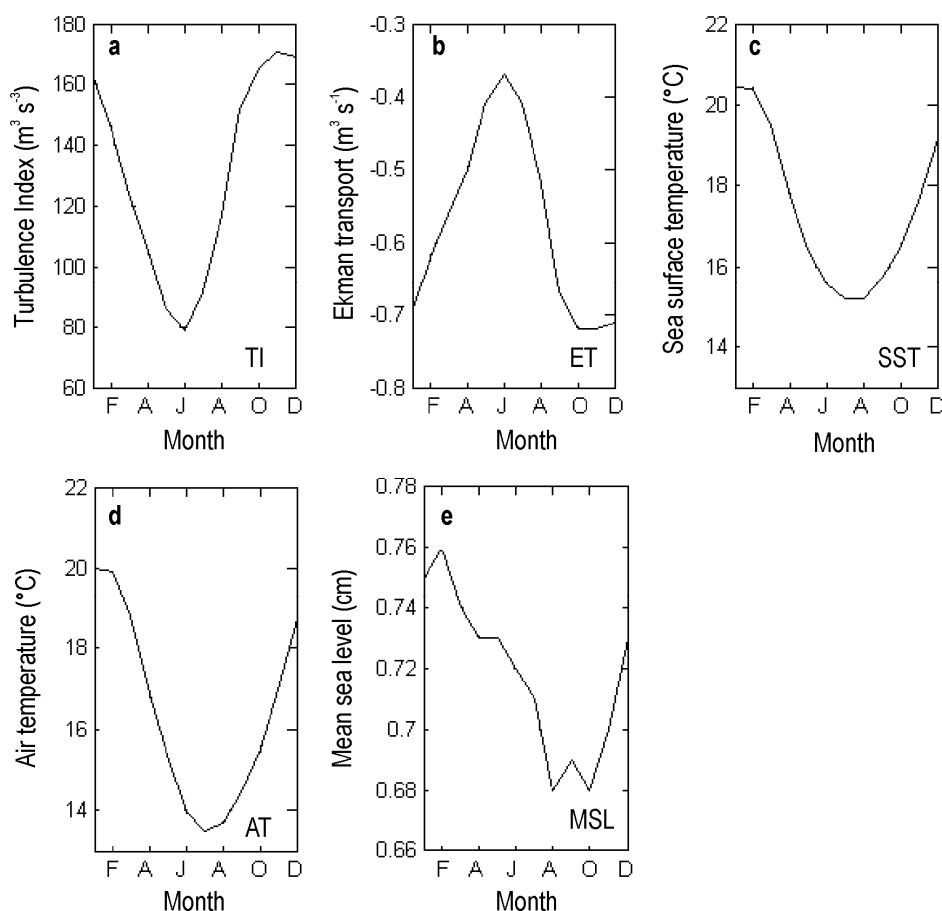


Figure 4. Monthly changes of a) turbulence index (TI), b) Ekman transport (ET), c) sea surface temperature (SST), d) air temperature (AT), and e) mean sea level (MSL), estimated using data from coastal stations located in Antofagasta.

Figura 4. Variación mensual del a) índice de turbulencia (IT), b) transporte de Ekman (TE), c) temperatura superficial del mar (TSM), d) temperatura del aire (TA), y e) nivel medio del mar (NMM), estimada con datos de estaciones costeras de Antofagasta.

For the anchovy fishery (1957-2002), the EOF analysis of combined variables allowed us to extract a first principle component (PC1) that explained 58% of the variability (Fig. 12a). The variables individually explained: catch (54%), fishing effort (59%), ET (65%), and TI (55%). The analysis of the sardine fishery (1974-1995) considered a PC1 that explained 62% of the variability (Fig. 12b). In this case, the variables individually explained: recruitment (77%), biomass (83%), SST (48%), and ET (52%).

Environment defined by remote equatorial forcing

An index of the environmental fluctuations was defined using the PC1 of the smoothed and normalized series (by the standard deviation) of the SST, ASL, Zb, and AT (Fig. 13). This mode explained 91% of the

variance and was related to the normalized anchovy and sardine landings. According to the analysis, the CP1 explained 68% of the variance (Fig. 14a) and was similar to the environmental index (Fig. 13a), with a correlation of 0.92.

The PC2 explained 21% of the total variance, showing a positive tendency between the 1960s and the 1990s (Fig. 14b). As can be seen in Fig. 14c, on the main axis, the anchovy and sardine fisheries presented opposing variations, favoring a “positive” environment for sardine landings and a “negative” environment for anchovy landings. On the other hand, these two fisheries presented similar fluctuations on the second axis, increasing their landings when the values on the axis were positive.

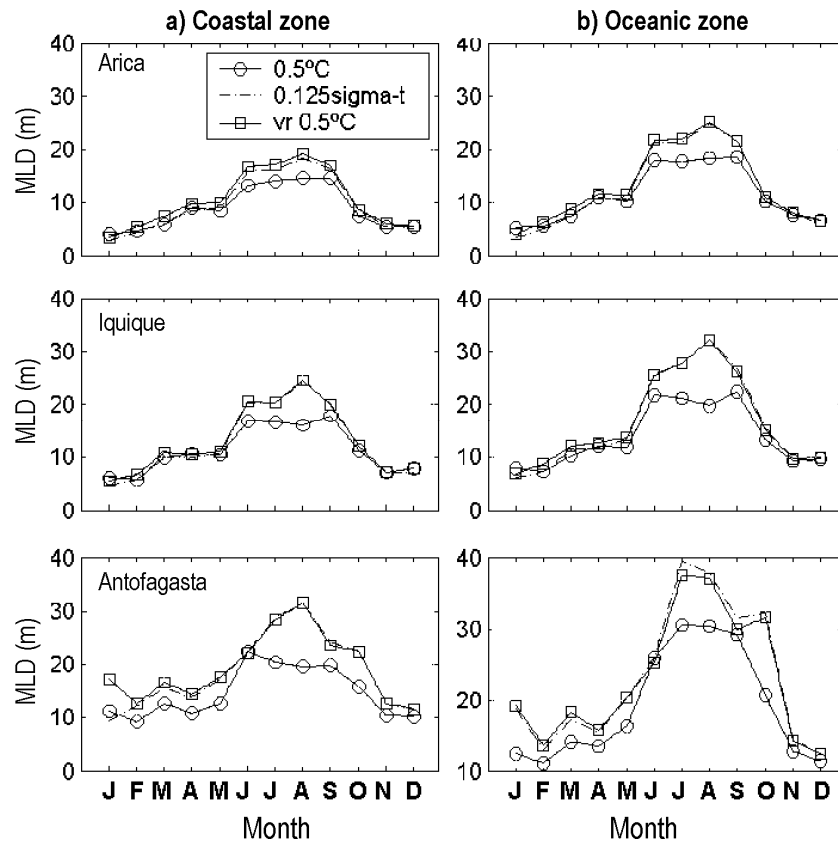


Figure 5. Monthly changes of mixed layer depth (MLD), estimated using KARA algorithm (2000) and hydrographical series from 1965 and 1998 observed in a) coastal, and b) oceanic zones of northern Chile, using three different criteria (0.5°C; 0.125σ_t and vr 0.5°C).

Figura 5. Variación mensual de la profundidad de la capa de mezcla (PCM), calculada utilizando el algoritmo de Kara (2000) y la serie hidrográfica comprendida entre 1965 y 1998 para la a) zona costera, y b) zona oceánica del norte de Chile, utilizando tres criterios (0,5°C; 0,125σ_t y vr 0,5°C).

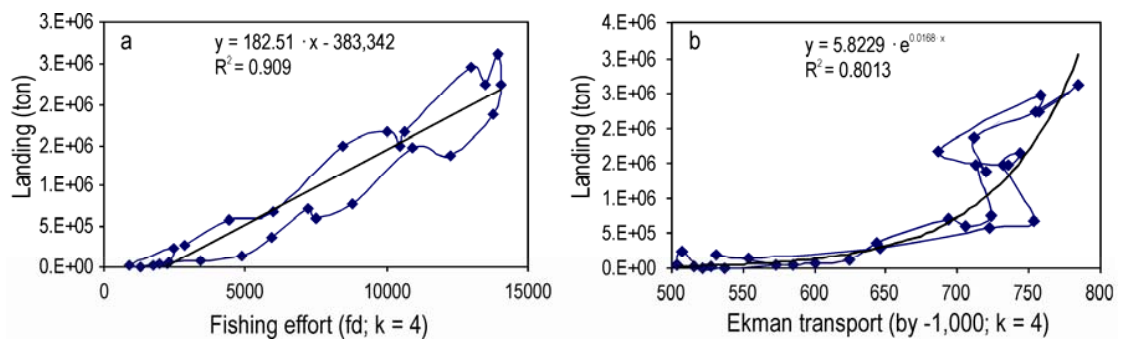


Figure 6. Sardine landings in relation to a) effort data, and b) Ekman transport in northern Chile (1973-2002).

Figura 6. Desembarque de sardina en función del a) esfuerzo de pesca, y b) transporte de Ekman en el norte de Chile (1973-2002).

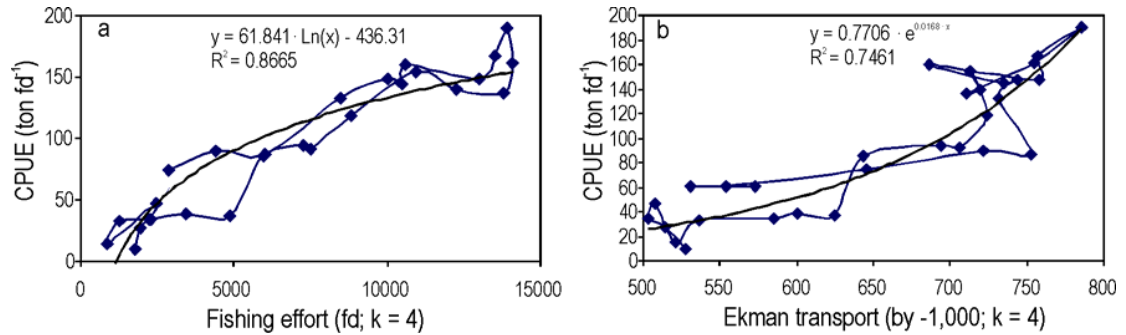


Figure 7. Sardine CPUE in relation to a) effort data, and b) Ekman transport in northern Chile (1973-2002).

Figura 7. CPUE de sardina en función del a) esfuerzo de pesca y b) transporte de Ekman en el norte de Chile (1973-2002).

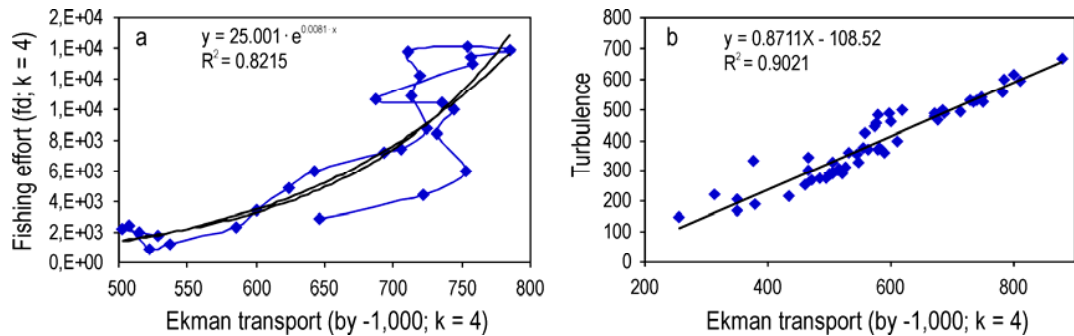


Figure 8. CLIMPROD models for a) sardine effort data (1973-2002), and b) turbulence (1950-2002) in relation to and Ekman transport in northern Chile.

Figura 8. Esfuerzo de pesca de sardina a) (1973-2002) y turbulencia b) (1950-2002) en función del transporte de Ekman en el norte de Chile.

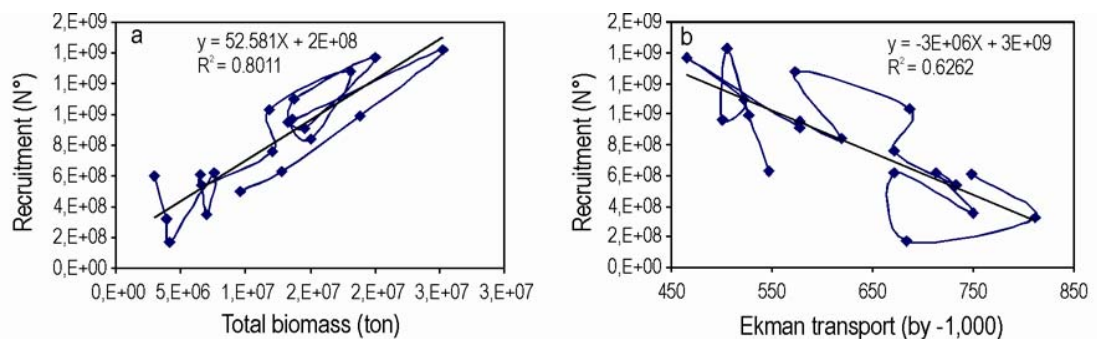


Figure 9. Anchovy recruitment in relation to a) biomass, and b) Ekman transport in northern Chile (1984-2002).

Figura 9. Reclutamiento de anchoveta en función de la a) biomasa, y b) transporte de Ekman en el norte de Chile (1984-2002).

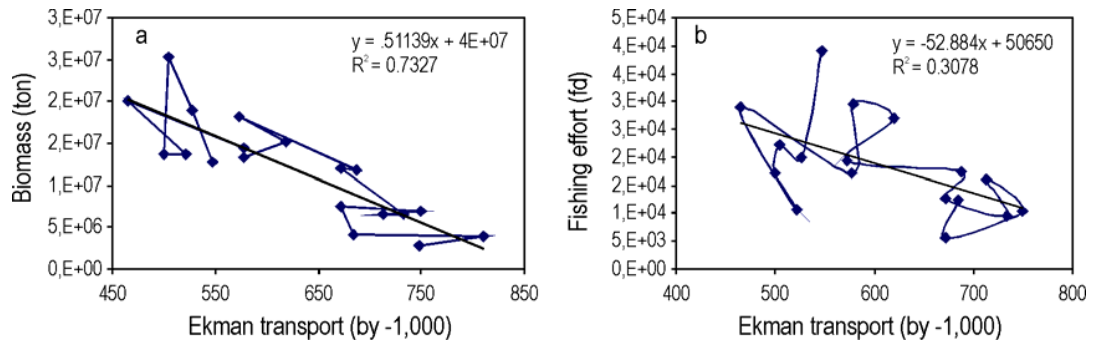


Figure 10. CLIMPROD models for a) anchovy biomass, and b) effort data in relation to Ekman transport in northern Chile (1984-2002).

Figura 10. Modelos CLIMPROD a) Biomasa de anchoveta, y b) esfuerzo de pesca en función del transporte de Ekman en el norte de Chile (1984-2002).

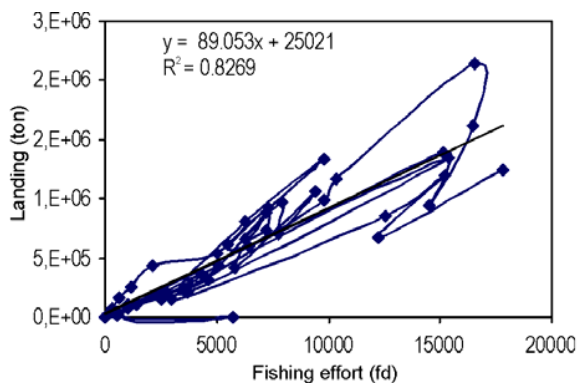


Figure 11. Anchovy landings in relation to effort data in northern Chile (1957-2002).

Figura 11. Desembarque de anchoveta en función del esfuerzo de pesca en el norte de Chile (1957-2002).

Conceptual model

Considering the different analyses carried out and the bibliographic information mentioned, we adapted an integrated conceptual model of the changes that were produced on different spatial-temporal scales (Fig. 15).

Interdecadal scale

Evidence of regime shifts was clearly observed when studying the decadal variability of the anchovy and sardine abundance proxies off northern Chile. Consequently, in this ecosystem, we observed alternating periods dominated by anchovy and sardine (Fig. 1). We defined regime shifts to be the critical transition periods between an ecosystem dominated by anchovy and another dominated by sardines (Fig. 12).

The first period (1950-1971) was favorable to the anchovy fishery, given the high fishery efforts (FE AN) and landings (LAN AN) recorded in the 1960s and 1970s. This period was characterized by positive SOI values and a comparatively cold environment (reflected in the AT and SST), with an ASL that tended to decrease, moderate winds (reflected in the ET and TI), and a shallow Zb (Fig. 12, Fig. 13, and Table 2a). A shift in the ecosystem regime was observed in the beginning of the 1970s with the onset of the 1972-1973 El Niño events and associated with heavy fishing pressure. As a result, the anchovy abundance decreased due to low recruitment caused by the diminished parental biomass.

The second period (1973-1987) favored the sardine fishery, as seen in the high fishery efforts (FE SAR) and landings (LAN SAR); anchovy landings were also important as of 1986 (Figs. 1a and 12). In this period, the SOI in general decreased, the environment was comparatively warmer (reflected in the SST and AT), the ASL was greater, and the Zb deepened; local winds increased and, therefore, so did the ET and the TI (Fig. 13, Table 2b). A second regime shift was observed in the ecosystem at the end of the 1980s, with a shift from a sardine-dominated system to an anchovy-dominated system; the latter prevailed through the writing of this study (July 2007).

The third period (1989-2002) was again favorable for anchovy, with high biomass (B-AN), recruitment (R-AN), fishery efforts (FE AN), and landings (LAN AN), unlike those observed for sardine (Table 2c). Although the AT did not tend to recover its previous cold levels and the SOI tended to recover positive values only at the end of the period (except for 1988-1989), the characteristics corresponded more to those

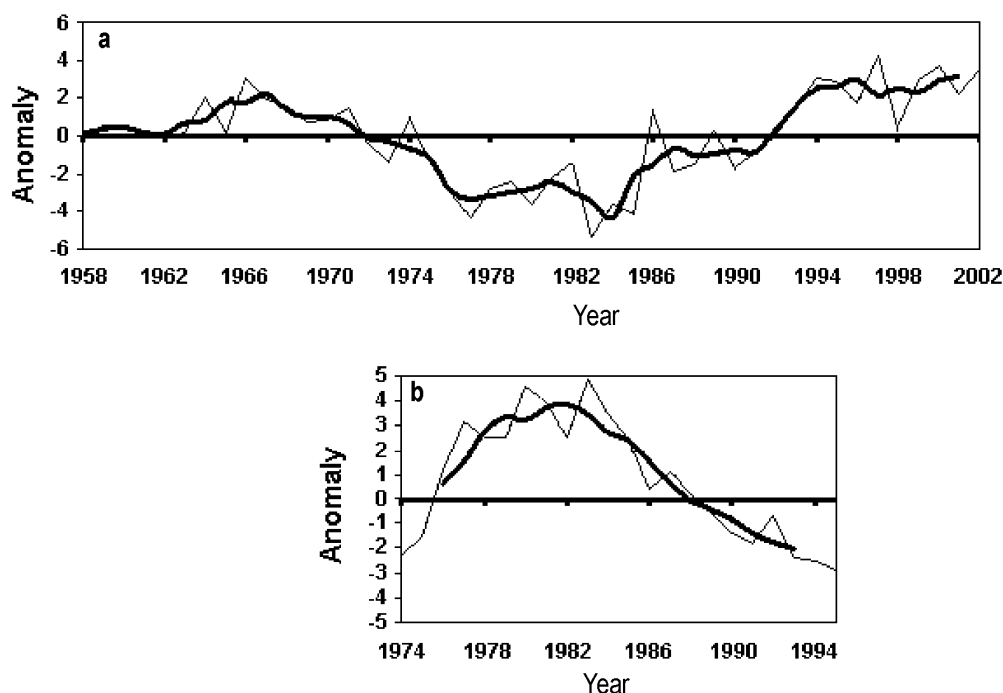


Figure 12. First principal component of a) catches, effort, Ekman transport and turbulence for anchovy (PC Mode 1, 58%), and b) recruitment, biomass, sea surface temperature and Ekman transport for sardine (PC Mode 1, 61.5%). Thick line represents the filtered series.

Figura 12. Primera componente principal de las series de a) captura, esfuerzo de pesca, transporte Ekman e índice de turbulencia para anchoveta (PC Mode 1, 58%), y b) reclutamiento, biomasa, temperatura superficial del mar y transporte Ekman para sardina (PC Mode 1, 61.5%). La línea gruesa representa las series filtradas.

of a cold environment, with local variables (SST, NM, ET, TI) that clearly tended to decrease.

Interannual scale

During El Niño events, the SOI decreased, temperatures were high at the Equator regions El Niño 1-2 and El Niño 3-4, and in the study area (SST, AT), the ASL increased, and the Zb deepened (Table 3a). Under these conditions, the anchovy abundance (as measured by acoustics (sA)), the quantity of eggs (EGGS), decreased (at least in 1997) along with the and the distance from the coast (DC); hence, the species dispersal and vertical distribution increased. At the same time, the anchovy fishery efforts (FE AN) and landings (LAN AN) diminished noticeably.

During normal-cold years, these conditions were completely inverted (Table 3b). The SOI strengthened, temperatures at the Equator (El Niño 1-2, El Niño 3-4) and in the study area (AT, SST) dropped, the ASL declined, and the Zb became shallower. Under these conditions, particularly during long-term cold periods (prior to 1976, after 1990), the anchovy biomass, egg

quantity, DC, FE-AN, and LAN-AN increased; anchovy vulnerability also increased due to the effect of the shallower Zb.

Seasonal scale

In the study area, the average monthly SST was higher during El Niño events (Figs. 16a and 16b). In summer, the SST was high, tended to decrease in autumn, reached its lowest levels in winter, and then recovered in spring. During normal-cold years, chlorophyll was higher in summer and minimum in winter; during El Niño events, the summer maxima decreased noticeably.

The thermal horizontal gradients (GRT) in the anchovy distribution were greater in spring-summer and lesser in winter, particularly during normal-cold years (Fig. 16a). In the sardine distribution, the gradients were steeper in summer-autumn, particularly in normal-cold years; after this they decreased and remained low until the end of the year (Fig. 16b). With the exception of summer, the gradients during El Niño events were lesser, particularly in winter-spring.

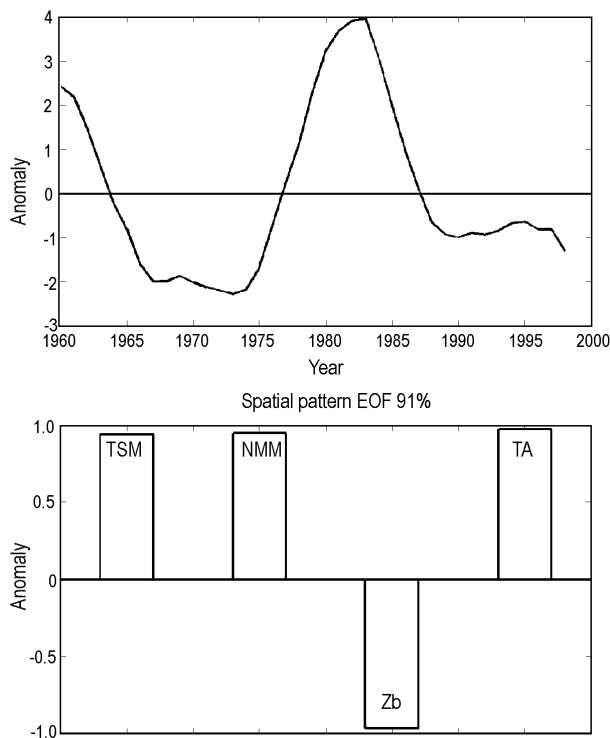


Figure 13. a) First principal component (91%) of smoothed and normalized series (standard deviation) of SST, MSL, Zb and AT during the 1960-1998 period, b) the first proper vector, as well as the correlation of the first principal component and the respective series.

Figura 13. a) Primer componente principal (91%) de las series suavizadas y normalizadas (por la desviación estándar) de TSM, NMM, Zb y TA en el periodo 1960-98, b) primer vector propio como la correlación de la primera componente principal y las series respectivas.

Anchovy were mainly distributed within 25 nautical miles (nm) of the coast in summer-autumn; in winter-spring, the distance from the coast (DC) increased noticeably, with specimens reaching 35 nm (Fig. 16a). During El Niño events, the distribution was rather coastal in summer and later surpassed 25 nm from the coast on occasions. In normal-cold years, the average DC for sardine was between 25 and 35 nm from the coast in summer-autumn, and from 45 to 55 nm in winter-spring (Fig. 16b). During El Niño events, sardine were also found from 25 to 35 nm in summer-autumn, but in winter-spring their distribution was more coastal (30-45 nm).

The anchovy CPUE did not show a clear seasonality in the study period, although it was slightly greater in summer (Fig. 16a). During El Niño, the CPUE was slightly greater in summer-autumn-winter than during normal-cold years. The sardine CPUE in normal-cold

periods showed its highest values in spring (Fig. 16b). During the El Niño events, the CPUE was noticeably elevated in summer-autumn-winter, indicating a greater availability due to the approaching warmer waters.

Interannual and seasonal scale

During El Niño events, the isotherms and the distribution of anchovy deepened. The greater anchovy densities (aggregation fish core) were typically found at an average depth of 15 m, with a vertical excursion that did not exceed 60 m during El Niño periods (Fig. 17). The anchovy tend to expand their vertical distribution during these periods, reaching an average maximum depth near 140 m (Fig. 17).

During the study period the fluctuations of ASL and the subsurface Peru-Chile current were strongly modulated by the dynamic of the equatorial waves (Pizarro *et al.*, 2002; Hormazabal *et al.*, 2002). At intraseasonal frequencies, the coastal-trapped waves are dominating (Shaffer *et al.*, 1997; Hormazabal *et al.*, 2002); on lower frequencies, during warm periods equatorially forced Rossby waves are dominating and during cold periods these waves appear to be forced by a combination of coastal wind and equatorial forcing (Hormazabal *et al.*, 2002; Hormazabal, 2003).

Daily-weekly scale

Off northern Chile, coastal upwelling prevailed throughout the year due to the predominance of south and south-west winds that had maximum values in summer and minimum values in winter (Pizarro *et al.*, 1994). Upwelling events lasted 4 to 15 days and their extension reached 40 nm; the longer events were produced at the end of summer and beginning of autumn, and the shorter events occurred in winter-spring (Barbieri *et al.*, 1995).

In spring-summer, upwelling was stronger due to the greater intensity of the favorable winds, the shallower thermocline (Zb), the more marked thermal gradients, and the productivity that was more concentrated at the coast (Fig. 18). During the long-term cold periods, these spring-summer environmental conditions had a positive effect on the anchovy concentration and a negative effect on sardine. During long-term warm periods, the spring-summer environmental conditions negatively affected the anchovy concentration and positively affected sardine. On the other hand, in winter, the winds were weaker, the Zb deepened, the thermal gradients decreased in intensity, and productivity was more disperse. These conditions were accentuated during the cold years and were no

ticeably modified during El Niño and long-term warm periods.

DISCUSSION

Landings and CPUE

The anchovy yields showed negative anomalies associated with El Niño events (Yáñez & Barbieri, 1988), as reflected in their lower landings (Fig. 1a). Moreover, the drop in this fishery at the beginning of the 1970s coincided with the collapse of the recruitment observed before the strong 1972-1973 El Niño event

(Mendelsohn, 1989; Mendelsohn & Mendo, 1987). Anchovy biomass and catches off Peru also decreased prior to the 1972-1973 El Niño event (Alheit & Niquen, 2004). However, the sardine fishery began to grow in the mid-1970s associated with the decrease in the long-term SOI (Cañón, 1986; Fig 1b).

Off northern Chile, the succession of pelagic species, including ichthyoplankton (Loeb & Rojas, 1988), began in the early 1970s in association with a change in the local and global environmental indexes. After 1985, however, changes were observed in some local indexes such as SST and ASL and, although not clearly, in the SOI (Yáñez, 1998). In fact, after 1975, a

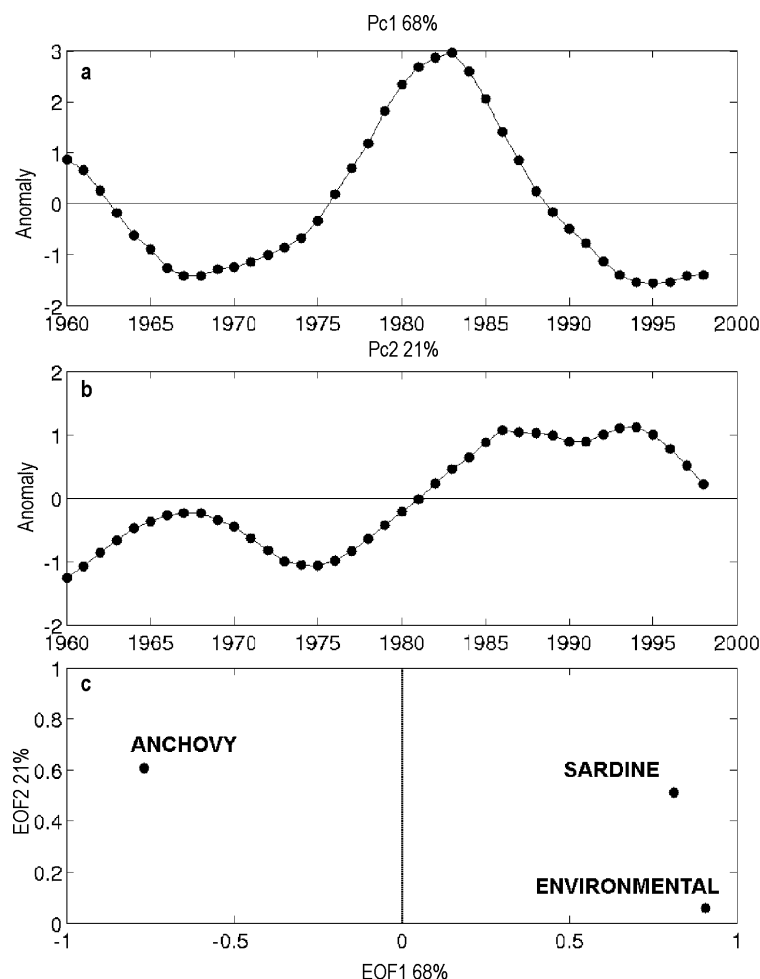


Figure 14. a) First principal component and b) second principal component of smoothed and normalized series (standard deviation) of environmental index (see Fig. 13) and anchovy and sardine landings during 1960-1998, c) dispersion diagram between the first and second proper vector, as well as the correlation of respective principal components and series.

Figura 14. a) Primer componente principal y b) segundo componente principal de las series suavizadas y normalizadas (por la desviación estándar) del índice ambiental (ver Fig. 13), y los desembarques de anchoveta y sardina en el periodo 1960-1998, c) diagrama de dispersión entre el primer y segundo vector propio, como la correlación de las respectivas componentes principales y las series respectivas.

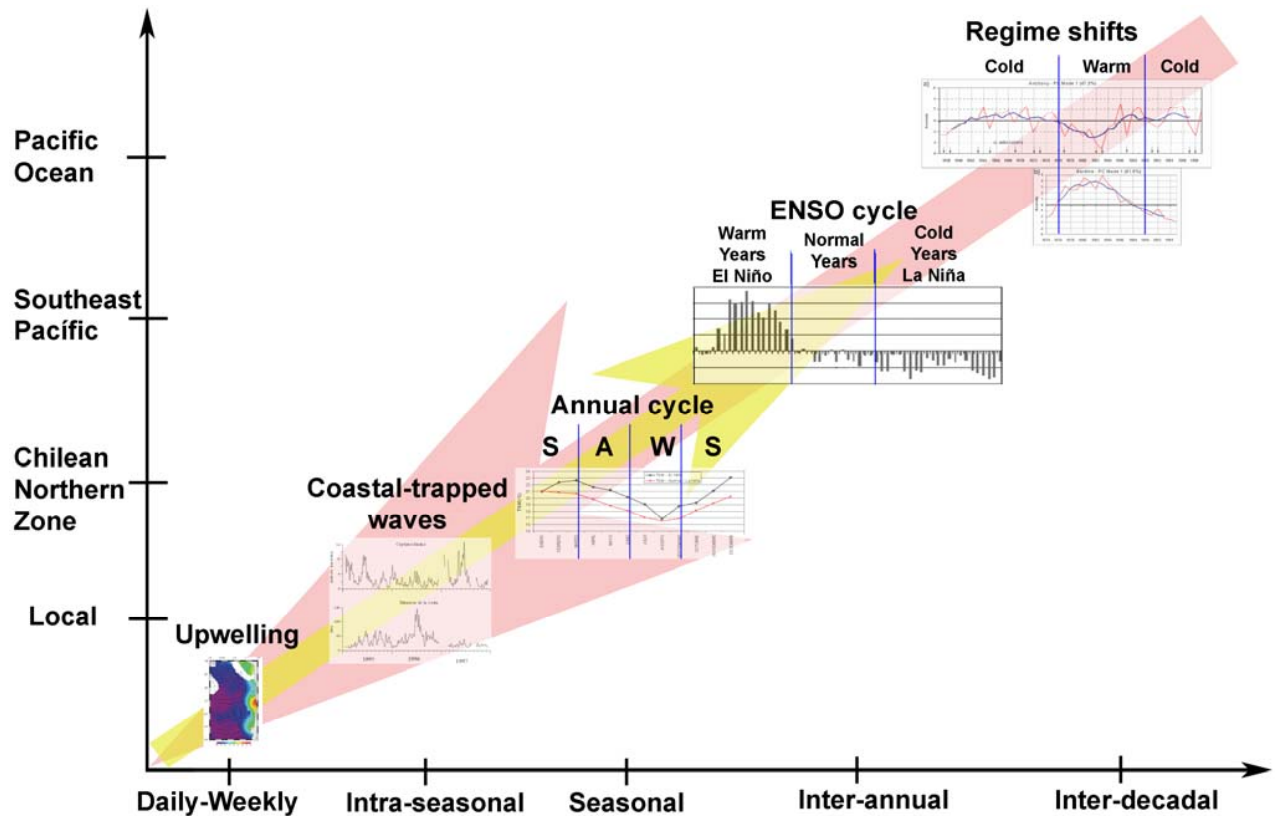


Figure 15. Integrating conceptual model of local and large-scale phenomena affecting northern Chile and main fishing resources. The arrows show the direction and magnitude of the phenomena influence. S: summer, A: autumn, W: winter, and S: spring.

Figura 15. Modelo conceptual integrador de los fenómenos locales y de gran escala que afectan la zona norte de Chile y sus principales recursos pesqueros. Las flechas indican el sentido y magnitud de la influencia de los fenómenos. S: verano, A: otoño, W: invierno, y S: primavera.

warm period persisted in the area that was related to the increased abundance of sardine, heavy predators of anchovy eggs (Santander *et al.*, 1983). Towards the end of the 1980s, the colder conditions were reestablished that favored the recovery of anchovy and the decline of sardine in spite of El Niño events in 1987, 1991-1992, and 1997-1998 (Yáñez *et al.*, 2001).

We recommend prudence with the CPUE estimates, due mainly to the difficulty in separating the variations in abundance from availability. Furthermore, the operational information from the vessels considered days with fishing but did not identify the sites of activity of the vessels that returned without catch. Nonetheless, the annual anchovy CPUE for northern Chile (1986-2003), calculated considering trips with fishing and total trips, presented a similar decreasing tendency (Anónimo, 2004).

In spite of the El Niño events of 1987, 1991-1992, and 1997-1998, the environmental conditions in the

north of Chile presented a cooling tendency towards the mid-1980s that favored anchovy (Yáñez *et al.*, 2003). The relationship between the CPUE and anchovy biomass may have been influenced by, among others things, increments in vulnerability when faced with adverse environmental scenarios (Alheit & Niquen, 2004) and technological changes in the fleet that were not entirely included in the standardization models (Punt, 2000).

It should be pointed out that the anchovy CPUE off northern Chile (Anónimo, 2004) presented a different tendency than the VPA-estimated biomass (Serra *et al.*, 2004). In fact, in an examination of the $CPUE = q B^\beta$ relationship, using anchovy biomass estimated with EPM, the parameter $\beta = 0.55$ indicated a bias when considering the CPUE proportional to the abundance.

On the other hand, the sardine CPUE estimates seemed to be more reasonable, with growth to the mid-1980s followed by a clear decrease (Anónimo,

2004). However, the VPA-estimated biomass indicated that the decrease began earlier (Serra & Canales, 2003), which also implied a certain degree of hyper stability of the CPUE.

Anchovy are largely distributed in the first 30 nm from the coast, are small (18 cm), short-lived (4 years), and have high fecundity. On the other hand, sardine are larger (42 cm), live longer (11 years), have lower fecundity, and are more oceanic in distribution (Serra, 1983; Serra & Tsukayama, 1988; Yáñez *et al.*, 2001).

The summer increments in anchovy CPUE and landings are associated with the secondary spawning and the important process of recruitment (Braun *et al.*, 1995; Castillo *et al.*, 2002), protected since 1986 by bans on extraction (Table 1). The increase in winter is associated with the secondary recruitment period; the main spawning period occurs after a break in sexual activity from March to May (Braun *et al.*, 1995). It should be noted that the bans applied since the mid-1980s are effective from July to September (Table 1).

Sardine normally present prolonged spawning from July to March, with an intense period from August to September and another less intense period from February to March (Serra & Tsukayama, 1988; Martínez *et al.*, 1992). Since 1983, these periods have been protected by extraction bans (Table 1).

Under extreme environmental conditions, such as those associated with the El Niño phenomenon, drastic alterations are produced in the magnitude and season of the spawning peak of these resources off northern Chile (Martínez *et al.*, 1986). When subtropical waters do not invade the region, waters with subantarctic origins dominate and favor upwelling, creating a suitable situation for anchovy. Under normal conditions, anchovy do not generally surpass 50 m depth and, horizontally, they are found within 50 nm of the coast given the warm conditions and less food available in the exterior waters (Yáñez, 1989). The intrusion of subtropical waters modifies the environmental conditions, affecting the anchovy behavior. Thus, El Niño events diminish anchovy catches, affecting resource availability and vulnerability. These events affect fecundity and egg viability and the survival of larvae, post larvae, and juveniles; they also decrease recruitment and stock biomass (Chavez *et al.*, 2003).

The seasonality of the TI and ET are associated with coastal winds that are less intense in winter and more intense in spring-summer. Nonetheless, the annual cycle of oceanic wind obtained from satellite data differs from that of the coastal wind, being more intense in winter and less intense in summer, producing negative Ekman pumping in summer (Hormazábal *et*

al., 2001). This limits the extension of the upwelling events to a narrow coastal band, concentrating the anchovy near the coast and making them more vulnerable.

This is related to the annual cycle of satellite chlorophyll-*a*, which, along the coast, is at its highest in the summer and at its lowest in the winter (Yuras *et al.*, 2005). In the oceanic sector, the cycle is the opposite, allowing a greater horizontal extension of the area of anchovy distribution in winter due to higher food availability. The anchovy landings and CPUE drop from July to October, possibly associated in part with the greater depth of the mixing layer. An increase in the MLD implies a greater vertical extension of the resource, which makes it less accessible to the fishing fleet.

Environment defined by the local winds

Pizarro & Montecinos (2004), Montecinos & Pizarro (2005), and Montecinos *et al.* (2005) established that the fluctuations in the environment off northern Chile, on an interdecadal scale, are mainly forced by changes in the Trade Winds in the equatorial Pacific. Thus, oceanic changes off northern Chile are produced by variations in the Zb that are related to equatorial fluctuations. The deepening (rising) of the Zb implies an increase (decrease) of the ASL and an increase (decrease) of the SST due to a decrease (increase) in the vertical advection of the relatively cold waters.

After certain levels, increased turbulence and Ekman transport, which are closely correlated, do not favor anchovy production (Yáñez *et al.*, 2001). Egg and larvae mortality are greater and, therefore, recruitment is lower due to the dispersal and modification of the food quality (Bernal *et al.*, 1983; Santander & Flores, 1983), and an increase in the seaward transport of the reproduction products (Parrish *et al.*, 1983). Nevertheless, an effect on the catchability cannot be excluded, particularly on older individuals able to modify their distribution.

The augmented sardine abundance off northern Chile was associated with a regime shift that began in the early 1970s and was reflected in increased local variables and a decreased SOI (Yáñez, 1998). This warm period likely favored the increased intensity of sardine spawning and recruitment until wind intensities surpassed those that maximize anchovy recruitment (Yáñez *et al.*, 2001). These healthy recruitments favored the increase of 5 to 8-year-old sardine individuals, the most represented in the catches. Food availability for these specimens is good due to the greater Ekman transport and the absence of a considerable anchovy biomass.

Nonetheless, since 1985, large anchovy egg and larval abundances have been seen again (Rojas, 1986; Loeb & Rojas, 1988), along with an extraordinary growth in their catches, which were affected by the El Niño events of 1987, 1991-1992, and 1997-1998 (Fig. 1a). This recovery was related to the tendency towards environmental cooling after 1987, the decrease in ET and TI to average values, and the decreased sardine abundance (Yáñez *et al.*, 2003). In fact, after the peak observed in 1984, the sardine recruitment decreased linearly with the parental biomass and with the average SST of year i to $i-2$ (Yáñez *et al.*, 1998), which was then reflected in the noteworthy decrease in the catches (Fig. 1b). On the other hand, zooplankton volumes recorded in 1973 and 1985 were low but recovered notably towards the end of the 1980s (Ayon & Guevara, 2004).

The two periods favorable to the anchovy fishery were separated by a negative period that coincided with an environment that favored sardine abundance and the development of its fishery (Fig. 12). The same regime shifts identified herein were proposed for explaining the succession of pelagic species off northern Chile, as well as the changes in common sardine, anchovy, hake, jack mackerel, and swordfish off central Chile (Yáñez *et al.*, 2003). Chavez *et al.* (2003) indicated that the fluctuations of anchovy and sardine in the Pacific were associated with large-scale changes in oceanic temperature, identifying two cycles with two cold phases (1900-1925, 1950-1975) and two warm phases (1925-1950, 1975-1995).

Environment defined by remote Equatorial forcing

Eighty-nine percent of the interdecadal variability of the landings, representing an abundance index on this temporal scale, could be explained by the variability of an environment defined basically by fluctuations in the Zb (68%) and fishing effort (21%). Nonetheless, although it was possible to find reasonable explanations for the relationship between the fisheries and the fluctuations of the environmental variables, we must consider that the magnitudes of the changes in these variables were small.

In fact, these amplitudes were on the order of 0.8°C in the case of SST, 10 cm for ASL, and 10 m for Zb. The question then arises as to whether or not it is possible to produce a change in the pelagic fisheries with these environmental variations. This requires a further the analysis of the life cycle of these pelagic species and determining which phase of this cycle is

more susceptible to being modified by the environmental variations on the interdecadal scale.

Integrating conceptual model

A conceptual model was adapted to show how the interdecadal (associated with regime shifts) and inter-annual (associated with El Niño events) fluctuations in the equatorial Pacific are manifested in the southeastern Pacific and, therefore, off northern Chile affecting, amongst others, the dynamic of the equatorial waves, the annual cycle, and coastal upwelling.

In the interdecadal period analyzed, three periods were observed that are associated with two regime shifts. The first, early in the 1970s, began along with the 1972-1973 El Niño event; the second, produced around the 1990s, began in the mid-1980s. The fluctuations in the bio-fishery and environmental variables available for this interdecadal period characterize the three periods in question (Table 2). The most notable biological fluctuation is the substitution sequence of the species under study (Fig. 1).

On the interannual scale, significant changes were produced by El Niño events, which "heated" an environment with rather cold characteristics (Table 3). Long-term warm and cold periods were also observed on the interdecadal scale. The El Niño phenomenon was amplified when developed during long-term warm periods (1973-1987), which can be seen in the SST, ASL, and AT of the 1982-1983 event, without detracting from the high values that these variables presented during the strong 1997-1998 El Niño (Yáñez *et al.*, 2003).

The high sardine landings were more related to the establishment of a long-term warm period (1973-1987) than with El Niño events that occurred within this period (Fig. 1b). In fact, after the 1972-1973 El Niño event, sardine increased noticeably in the spawning and larval distribution areas, even establishing a spawning center off Talcahuano (Bernal *et al.*, 1983).

Bernal *et al.* (1983) indicated that eastern boundary systems, aside from the low-frequency fluctuations, have a clear and definable seasonality. In the present work, this variability is conceptualized by analyzing the fishery (CPUE, distance from the coast) and satellite data, duly geo-referenced for the 1987-2002 period (Fig. 16). As effects, we considered the resources in normal-cold years and during El Niño events of the study period. The most outstanding fact is the spatial segregation of the species and their concentration at the coast during El Niño events, particularly in winter-spring, when the thermal gradients are lower.

Table 2. Environmental and biofishery characteristics for three periods deduced from the temporal interdecadal analysis. The direction of the arrows indicates whether the variable values are high (↑) or low (↓), or tending to increase (↗), decrease (↘), or remain the same (→).

Tabla 2. Características ambientales y biopescuarias de tres periodos deducidos del análisis temporal interdecadal. El sentido de las flechas indica si los valores de las variables son altos (↑), bajos (↓), tendientes al alza (↗) o a la baja (↘), o se mantienen (→).

Variable	Abbreviation	a) 1950-1971	b) 1973-1987	c) 1989-2002
Southern Oscillation Index	SOI	↑	↓	↗
Air Temperature	AT	↓	↑	→
Sea Surface Temperature	SST	↓	↑	↘
Average Sea Level	ASL	↘	↑	↘
Turbulence Index	TI	→	↑	↘
Ekman Transport	ET	→	↑	□
Depth of thermocline base	Zb	↑	↓	□
Anchovy Biomass	B-AN	↑	↓	↑
Sardine Biomass	B-SAR	↓	↑	↓
Anchovy Recruitment	R-AN	↑	↓	↑
Sardine Recruitment	R-SAR	↓	↑	↓
Anchovy Landing	LAN-AN	↑	↓	↑
Sardine Landing	LAN-SAR	↓	↑	↓
Anchovy Fishing Effort	FE-AN	↑	↓	↑
Sardine Fishing Effort	FE-SAR	↑	↑	↓
Sardine Catch Per Unit Effort	CPUE-SAR	↓	↑	↓

Table 3. Environmental and biofishery characteristics during El Niño events and normal-cold periods. The direction of the arrows indicates whether the variable values are high (↑) or low (↓), or tending to increase (↗), decrease (↘), or remain the same (→).

Tabla 3. Características ambientales y bio-pescuarias durante eventos El Niño y periodos normales-fríos. El sentido de las flechas indica si los valores de las variables son altos (↑), bajos (↓), tendientes al alza (↗) o a la baja (↘), o se mantienen (→).

Variable	Abbreviation	a) El Niño	b) Normal/Cold
Southern Oscillation Index	SOI	↓	↑
Niño 1,2 SST Index	Niño 1-2	↑	↓
Niño 3,4 SST Index	Niño 3-4	↑	↓
Air Temperature	AT	↑	↘
Sea Surface Temperature	SST	↑	↓
Average Sea Level	ASL	↑	↘
Depth of thermocline base	Zb	↓	↗
Acoustic Abundance	Sa	↓	↑
Eggs Number	EGGS	↓	↑
Coastal Distance	CD	↓	↑
Anchovy Landing	LAN-AN	↓	↑
Anchovy Fishing Effort	FE-AN	↓	↑

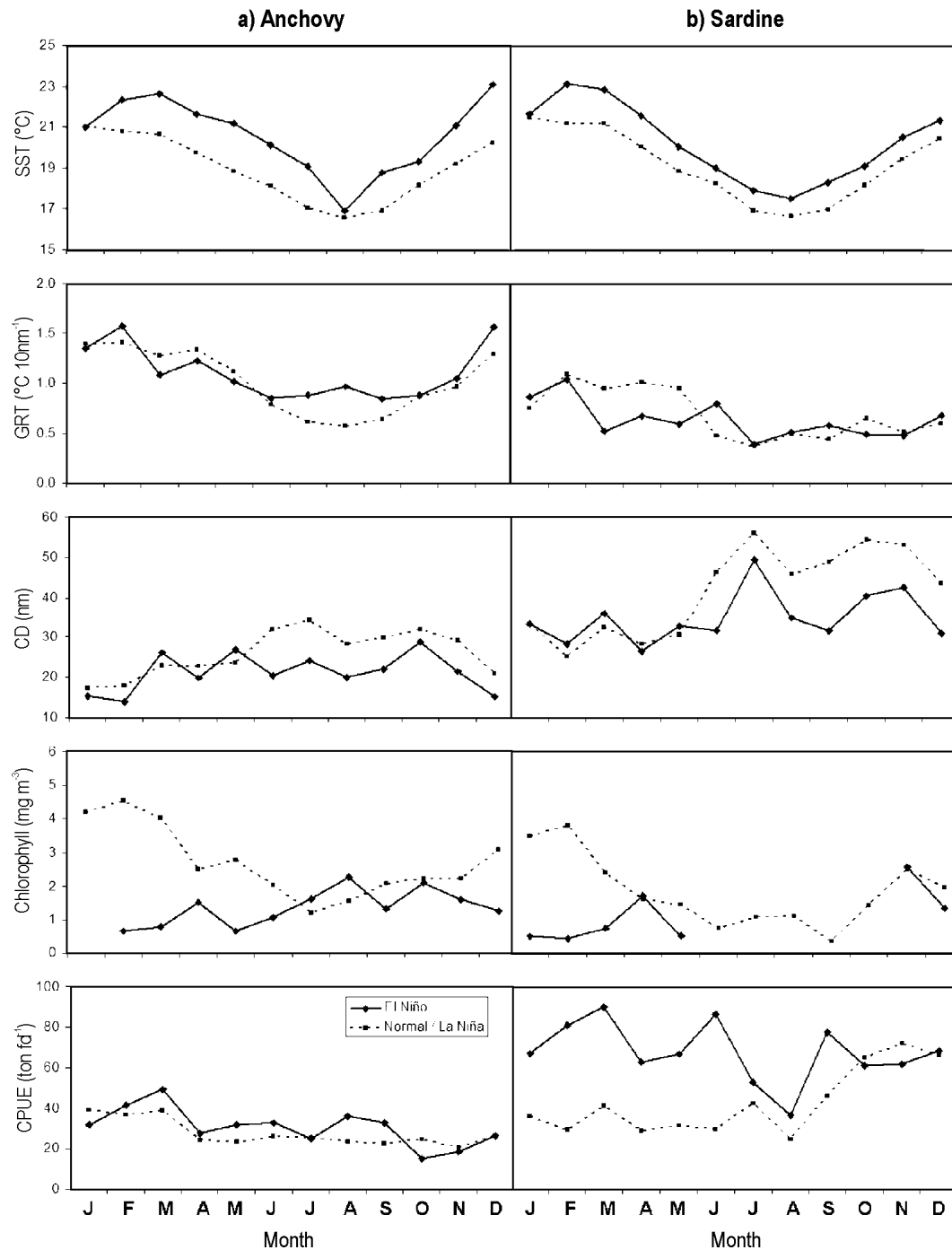


Figure 16. Characteristic annual cycle of a) anchovy, and b) sardine CPUE and environmental variables (SST, GRT, DC and chlorophyll) involved in catches. Annual cycle were defined taking into account two different environmental scenarios: El Niño events (1987, 1992 and 1997-1998) and normal/La Niña periods (1988-1991-, 1993-1996, 1999-2001).

Figura 16. Ciclos anuales característicos de la CPUE de a) anchoveta y b) sardina y variables ambientales (SST, GRT, DC y clorofila) asociadas a las capturas. Los ciclos anuales fueron obtenidos considerando dos escenarios ambientales, durante eventos El Niño (1987, 1992 y 1997-98) y años Normal/La Niña (1988-1991, 1993-1996, 1999-2001).

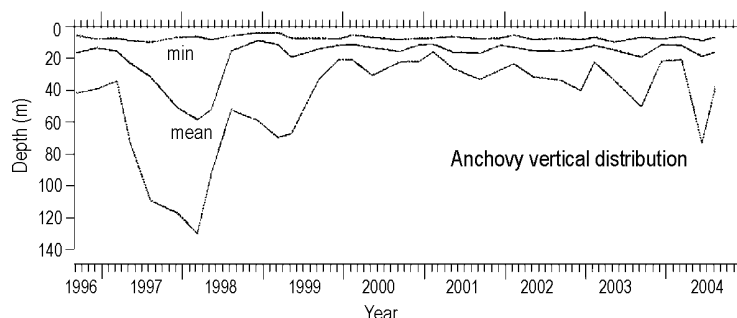


Figure 17. Time series of anchovy mean vertical distribution obtained during the acoustic exploration cruises of anchovy in northern Chile.

Figura 17. Series de tiempo del promedio de la distribución vertical de anchoveta obtenida de cruceros hidroacústicos de prospección de anchoveta en la zona norte de Chile.

The deepening of the thermocline during warm periods produced a change in the vertical distribution of the anchovy, significantly decreasing their availability to the fishing gear, as reflected in the decreased catches normally observed during these warm periods (Fig. 1a). This modification of the vertical excursion of the anchovy is accompanied by a significant deepening of the isotherms and the upper limit of the oxygen minimum zone, as shown off Iquique in works by Morales *et al.* (1999) and Thomas *et al.* (2001), amongst others. This is related to the decreases associated with the low recruitment produced by the negative effect these warm periods have on reproduction and eggs and larval survival.

The normal spring-summer conditions favored anchovy reproduction, the recruitment that is produced the year before, and vulnerability to the fishing gear (Tabla 4). Given normal winter conditions, anchovy are distributed in a wider and more disperse zone, being less vulnerable.

El Niño events increase anchovy mortality during the first stages due to changes in the quality of food caused by less effective upwelling; their vulnerability also decreases due to changes in their horizontal and vertical distribution. These effects are reflected in the noticeably lower catches during such events (Fig. 1a). The recovery of the catches the following year is due to the great reproductive capacity of the anchovy under favorable conditions and greater stock vulnerability.

Long-term warm periods accentuate these conditions, which are unfavorable for anchovy, by increasing turbulence (that disperses the food) and Ekman transport (that advects reproductive elements westward). The nearness and permanence of warm waters

Table 4. Environmental and bio-fishery characteristics in a daily-weekly scale.

Tabla 4. Características ambientales y bio-pesqueras en escala diaria-semanal.

Spring - Summer	Winter
+ Upwelling	- Upwelling
+ Winds	- Winds
- Thermocline (shallow)	+ Thermocline (deep)
+ Gradients	- Gradients
+ Productivity (concentrated in coast)	- Productivity (disperse)
Long-term cold period favourable to anchovy:	
+ Concentration	- Concentration
Long-term warm period favourable to sardine:	
- Concentration	+ Concentration

in the zone favor the approach of sardine, their increased abundance under favorable conditions and, therefore, the development of the fishery.

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