International Consultations on the Establishment of the
South Pacific Regional Fisheries Management Organisation

Eighth International Meeting: SWG: Jack Mackerel Sub-Group
SP-08-SWG-JM-06

VARIABILITY OF THE CHILEAN JACK MACKEREL FISHING HABITAT IN THE SOUTHEASTERN PACIFIC OCEAN

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ABSTRACT

The environmental variability of Chilean Jack Mackerel (CHJM) fishing habitat located in the oceanic waters off central and southern Chile is studied with the use of physical and fisheries information from the last two-three decades.

The results suggest that major fishing habitat shows important meridional and zonal gradients based on the seasonal spatial distribution of mean SST, SSS and MLD for a three decades period. This zone is also affected by the upwelling system off central-southern Chile. It also shows the existence of an important interannual variability in the CHJM habitat, which is mainly linked to tropical warm/cold perturbations like El Niño/La Niña. Time-series plots reveal that SST in this region seems to be in an opposite phase to the tropical signal, and the EKE interannual variability seems to control the oceanic chlorophyll fluctuation off central Chile, showing the important role that mesoscale eddies and energetic meandering currents plays in this region.

Finally, the resource-environment information suggests a complex association between CHJM biomass and the environmental variability in both seasonal and interannual scales, mainly linked to coastal upwelling and tropical climatic-oceanographic indexes. Future studies should be performed to include the population dynamics, fishing effort and migrations to clarify and strengthen the associations between Chilean jack mackerel and the environmental dynamics in the Southeastern Pacific Ocean.

INTRODUCTION

Chilean jack mackerel (*Trachurus murphyi* Nichols) is a migrating pelagic species which inhabits the Southern Pacific Ocean, and constitutes the most important fishery for Chile. This species presents a wide distribution, revealing a fairy broad band from Chile to New Zealand and Tasmania (Bailey 1989, Elizarov *et al*. 1992, Gretchina 1998). According to Serra (1991) a single self-sustained population across Chilean waters has been established, which includes the oceanic fraction off central-southern Chile. Chilean jack mackerel exhibits a strong seasonal migration pattern (Serra 1991, Arcos *et al*. 2001), showing an offshore migration towards the reproductive oceanic habitat in early spring which extends along the Southeastern Pacific Ocean (SPO), but mainly in oceanic waters off central Chile from 82°W to beyond 90°W (Cubillos *et al*. 2008); and an onshore migration during the summer linked to coastal food availability. During fall and winter, jack mackerel aggregates in compact schools in coastal and oceanic waters off central Chile, and is therefore captured by the Chilean purse-seine fleet (Arancibia *et al*. 1995). Spawning mainly occurs from October to December, although it can extend from September to February (Grechina *et al*. 1998).

The environmental variability in the Southeastern Pacific Ocean (SPO) could be mainly explained by intra-annual fluctuations associated to the coastal upwelling seasonality (Strub *et al*. 1998; Leth & Shaffer 2001, Rutland *et al*. 2002), inter-annual variability related to warm/cold alternated events (El Niño/La Niña) (Shaffer *et al*. 1999, Hormazábal *et al*. 2001, Escribano *et al*. 2004), including long equatorial trapped Kelving waves, coastal trapped waves and Rossby waves (Strub *et al*. 1998, Fuenzalida *et al*. 2008), and decadal variability (Klyashtorin 1998, McFarlane *et al*. 2000, Yáñez *et al*. 2002). It is also suggested that mesoscale structures (eddies, meanders and fronts) can play an important role in pelagic fish abundance and distribution (Nakata *et al*. 2000, Hormazábal *et al*. 2004, Núñez *et al*. 2006, Correa-Ramírez *et al*. 2007). These environmental fluctuations, observed at different scales of variability, can cause significant production and abundance changes and could be affect the abundance and distribution of fishery resources.

In this paper, we intend to describe the environmental variability of the Chilean Jack Mackerel fishing habitat off central-southern Chile, through the analysis of temporal and spatial fluctuations of environmental indexes obtained in this area during the last two-three decades.

DATA AND METHODS

Environmental data

The 4-km spatial resolution Sea Surface Temperature (SST) data was obtained as a result of diurnal measurements AVHRR Pathfinder Version 5.0 for 1985-2008 period available in ftp://data.nodc.noaa.gov. SeaWiFS chlorophyll satellite data (9-km spatial resolution) for 1997-2009 was obtained as a result of Oceancolor Web (www.seadas.gsfc.nasa.gov). The satellite current data was obtained by means a geostrophic balance from ¼ degree altimetry TOPEX-Poseidon and ERS satellite data distributed by AVISO (www.aviso.oceanobs.com). From geostrophic current information, the eddy kinetic energy field was also calculated for the fishing habitat of Chilean Jack Mackerel (CHJM).

Apart from satellite information, SST and sea surface salinity (SSS) from SODA (Simple Ocean Data Assimilation) a re-analysis model obtained from http://dsrs.atmos.umd.edu/ DATA/soda.2.0.4/ was used. This model has a 25 x 25 km spatial resolution and 40 levels in depth, and uses almost all of oceanographic data available for this re-analysis: NODC WDB-01 sub-surface salinity and temperature, several CTD stations, ARGO buoys data and XBT, temperature from thermistors TAO and PIRATA, and SST *in situ* and satellite data.

Hovmöhler plots were built with for mean spatial-daily chlorophyll, SST and EKE data, using an 1 degree amplitude band centered on 39ºS. Seasonal means were calculated from quarterly available SST and chlorophyll, considering the austral summer(winter) between December-February (June-August).

Fishery data

The 1996-2006 times-series of CHJM catches was analyzed through the fishing area daily location as used by Peña *et al*. (2001). For determining the fishing area locations and CHJM catches, three different data sources were used: fishing set statistics obtained from each vessel's fishing logbook, the geographical position of each vessel reported twice a day, the landings (in tonns) and the onboard observer reports. The catch data related to each fishing area was re-sampled by using a 10 x 10 km regular square.

The environmental thresholds were carried out during an acoustic cruise to assess CHJM biomass off central Chile in winter 2007 (Sepúlveda *et al*. 2009). Acoustic biomass was re-arrangement in 50 equal size intervals considering the environmental range for physical variables, which characterized the CHJM fishing habitat: temperature, sea level, vorticity, geostrophic velocity, thermocline depth, and surface density. A Gaussian function was fitted to the resulting biomass distribution by least squares, to determine statistical parameters (mean and standard deviation). Thus, the area confined between ± 1 standard deviation is considered as an optimum environment, where 70% acoustic biomass is concentrated (represented as vertical red lines in Figure 11).

RESULTS AND DISCUSSION

Chilean jack mackerel distribution in the southeastern pacific ocean

Chilean jack mackerel (*Trachurus murphyi* Nichols) constitutes the most important fishery in Chile. It has a wide spatial distribution extending from Ecuador to Southern Chile (52ºS), and from the Chilean coastal waters to New Zealand and Tasmania,. Its presence across the oceanic region is displayed as a fairly broad band (Bailey 1989, Elizarov *et al*. 1992, Grechina 1998). Russian scientists have refered to the distribution of CHJM in the SPO as "the belt of jack mackerel" by (Elizarov *et al*. 1992), recognizing a coherent association of increase in abundance and spatial westward expansion with an intensive development of CHJM fishery by the Russian fleet during the eighties (Nosov & Kalchugin 1990, Sokolov & Kuznetsov 1994, Elizarov *et al*. 1992, Grechina 1998). This colonization process was accelerated 2-4 years following drastic oceanographic changes linked to moderate and strong El Niño events in the SPO (El Niño 1982-

1983, 1986-1987). It is estimated that the jack mackerel commercial concentrations reached a western distribution boundary between 1987 and 1990 (Grechina 1998).

According to Serra (1991), this straddling resource exhibits a seasonal migration pattern characterized by a spring westward migration to oceanic habitat for spawning (spawning occurs between October and December), which extends across the Southeastern Pacific Ocean (SPO) but mainly occurring from ~82°W and beyond 92°W (Gretchina *et al*. 1998, Arcos *et al*. 2001, Sepúlveda *et al*. 2006, Cubillos *et al*. 2008). On the contrary, CHJM shows an eastward migration during the late summer related to coastal food availability, evidencing compact schools in coastal and oceanic waters off central Chile during fall and winter, and therefore accessible to the Chilean purse-seine fleet (Arancibia *et al*. 1995).

The results of the data recovered by the Chilean purse-seine fleet and biological-fisheries data for this species, demonstrate the existence of three spatially separated habitats for CHJM in the SPO (Arcos *et al*. 2001), and seasonal migrations in these zones indicate the seasonal behavior of fishing in the Chilean central-southern region. The following has been determined:: a) an oceanic reproductive habitat that includes the South Pacific eastern edge with a main spawning center extending between 33º-40ºS and from ~80-82 to beyond 92ºW (Núñez *et al*. 2004, 2006, Cubillos *et al*. 2008), b) an oceanic adult feeding area located within the 400 nm off central-south Chile, and c) a nursery habitat in the coastal and oceanic waters off southern Peru and northern Chile (within the EEZs), which shows highest concentrations of juveniles and pre-recruits, which is consistent with the juvenile phase of CHJM suggested by Elizarov *et al*. (1992), and recently named the CHJM nursery area (Grechina 1998, Arcos *et al*. 2001), which has a significant importance in the regional migratory circuit as a source of recruits to the central-south Chilean fishery specially during warmer oceanographic conditions (El Niño events).

The purse-seine fleet in central Chile experienced an important development during the last 25 years, reaching 85% of Chilean annual landings. This fishery experienced an important growth after 1986 reaching a maximum landing value of about 4.5 million tons in 1995. In following years, annual catches dropped drastically due to management regulations, establishing annual fishing quotas close to 1.3 million tons. Since 2002-2003, the spatial distribution of the purse-seine fleet showed a drastic westward displacement reaching fishing zones located beyond the Chilean EEZ, which intensified in 2008. This fishing zones displacement pattern experienced by the Chilean fleet has also ocurred in the case of the Chinese and European Community factory fleets that operate successfully in international waters adjacent to central Chile EEZ (Zhang *et al*. 2008, Corten 2008).

Chilean Jack Mackerel fishing grounds and catches for 1995-2008

The inter-annual variability of the purse-seine fleet's spatial distribution and the CHJM catches in the oceanic waters off central southern Chile is shown in Figures 1and 2. These figures show a regular pattern of CHJM spatial distribution until 2001, revealing that a high percentage of fishing zones are located within the EEZ and that over 50 % of catches were being obtained in the coastal zone (<75ºW). However, since 2002 a drastic change in this distributional spatial pattern was observed, confirming an evident and continuous westward displacement of fishing zones and a high percentage of catches in oceanic waters beyond the Chilean EEZ (> 78°W), reaching ~90ºW in 2008.

The climatology of CHJM catches for period 1995-2008 (Figure 3) shows high figures between late December and May, within ~200 Km from the coast. In these months, the purse-seine fleet activity does not exceed ~500 Km from the coast. On the contrary, a very low percentage of catches was observed from August-November, reaching up to 1300 Km from the coast in early September.

Environmental variability on the Chilean Jack Mackerel fishing habitat

Background

Along the coastal zone of Peru and Chile, the South Pacific Anticyclone push the winds equatorward in summer and poleward during late fall and winter (Saavedra 1980; Strub *et al*. 1998, Rutland *et al*. 2004). The persistence of S and SW winds produce an intense seasonal coastal upwelling leading to a rise in primary production and zooplankton, which can be exported to oceanic waters mainly through filaments and mesoscale eddies (Cáceres 1992, Thomas *et al*. 2001, Sobarzo & Figueroa 2001, Correa *et al*. 2007, Morales *et al*. 2008), and finally determine the spatial and temporal distribution and abundance of fishing resources.

Moreover, a strong inter-annual variability associated to alternated El Niño/La Niña events has been highlighted (Enfield 1989, Glantz 1996, McPhaden 2001), which produces an increment of SST and coastal sea level, an intensification of poleward current, a southward movement of inter-tropical convergence, a weakening of the Subtropical anticyclone, an increment of coastward transport, and the sinking of thermocline and nutricline (Rutlland & Fuenzalida 1991, Pizarro & Montecinos 2004, Maturana *et al*. 2004). A favored growth and reproduction of coastal zooplancton species is also suggested (Ulloa *et al*. 2001, Escribano *et al*. 2004, 2007). A low variability in zooplankton biomass has been mentioned as another possibility, as well as in primary production and vertical flow of carbon (Escribano *et al*. 2004), involving a re-analysis of the negative ENSO impact on the community structure and production, based on the rapid recovery of the global system of the highly productive Chilean upwelling system.

The circulation in the SPO is dominated by the anticyclonic Subtropical Gyre, which encompasses the westward South-Equatorial Current (north of 25ºS), the eastward South Pacific Current (between 30-40ºS), and the Chile-Perú Current flowing along the coast toward the Equator (Tomczak & Godfrey 1994, Leth 2000, Chaigneau & Pizarro 2005, Fuenzalida *et al*. 2008). The South Pacific Current has been confirmed to be an extension of the East Australian Current, and it is related to the Subtropical Convergence (or Subtropical Front, STF), which separates the warmer and saline subtropical waters from colder and less-saline sub-antarctic water. Southward of the STF, the eastward West Wind Drift Current and the Antarctic Circumpolar Current is related to strong westerly winds, transferring seawater properties between both the Pacific and Atlantic oceans.

Cheagneau & Pizarro (2005) also reveal surface eastward currents located westward 90ºW and south of 30ºS, showing an important latitudinal variability, surface velocities (~25 cm s^{-1}) at south of 50ºS associated with the SubAntarctic Front, a velocity decrement (~7 cm s^{-1}) related to SubTropical Front observed at 35ºS, a northeastward flows located between 40–55ºS and westward 110ºW, and a branch of northeastward current exporting sub-antarctic surface water to lower coastal latitudes (40ºS, 75ºW), being trapped into the Chile-Perú Current transferring relatively cooler and fresher water toward subtropical latitudes. Finally, an anticyclonic recirculation cell north of 35ºS is observed, where its southern, eastern and northern edges are linked with the South Pacific Current, the Chile-Perú Current and the South Eastern Current respectively, and the southern limit of the South Eastern Current is deflected southward and returns into the South Pacific Current between 104ºW and 120ºW (Strub *et al*. 1998, Leth & Shaffer 2001, Cheagneau & Pizarro 2005, Fuenzalida *et al*. 2008).

Environmental variability in the Chilean Jack Mackerel fishing habitat

Sea Surface Temperature (SST)

The spatial distribution of average SST in the CHJM fishing habitat off central-southern Chile shows a significant meridional gradient located between 30º to 45ºS especially offshore 85ºW, characterized by the 19°C and 10ºC isotherms domain. On the contrary, from equatorial region to ~30ºS a zonal gradient is observed, showing SSTs ranging between 20 and 23ºC (Figure 4a). A colder water coastal band is also observed at 30-38ºS, which is mainly linked to seasonal upwelling modulated by S-SW alongshore winds, and promoting the displacement of 14-17ºC isoterms to north; meanwhile the opposite occurs with a slight deviation of 10-14ºC isotherms to SE southward 39°S.

Moreover, seasonal SST fluctuations in the SPO show a similar distributional pattern between summer and autumn, and between winter and spring. Thereby, the comparison with the SST average distribution reveals a meridional isotherms displacement toward S-SE on summer-autumn period and to N-NE for winter-spring season. An increment (decrement) in the zonal gradient for autumn (spring) is also observed (Figure 4a).

Sea Surface Salinity (SSS)

The spatial distribution of mean SSS in the SPO and their seasonal distribution are presented in Figure 4b. This figures exhibit a salinity maximum (> 35 g kg^{-1}) linked to the subtropical waters located between 10º-30ºS, and a minimum (34 g kg^{-1}) associated to sub-Antarctic waters in the southeastern region (30º-50ºS). The front subtropical (FST) is located between these two water mass, associated with SSS values ranged between 34.3-34.8 g kg^{-1} (Stramma *et al*. 1995, Chaigneau & Pizarro 2005). On the SPO the maximum SS presents a main core located between ~18º-26º S and beyond 96ºW and, a northward low SS core is observed in the coastal region off Chile, generating a zonal SSS minimum at approximately 150 km offshore (Letelier *et al*., 2009). This SSS seasonal pattern shows differences between coastal and oceanic regions off central Chile. Within the Coastal Transition Zone (<600 km offshore, Hormazábal *et al*. 2004) the SSS is minimal in spring and maximal in autumn, while beyond this region, a minimum SSS in winter and maximum in autumn is observed (Letelier *et al*. 2009).

the geographical position and seasonal fluctuation of the SubTropical Front (STF) and SubAntarctic Front has been studied on the basis of SST and SSS spatial distribution, (Stramma *et al*. 1995, Chaegneau & Pizarro 2005, Letelier *et al*., 2009). Chaegneau & Pizarro (2005) pointed out that the STF can be mainly characterized by a meridional SSS variations, a maximum EKE values, and a meridional temperature gradient over 0-400 m, revealing a STF located between 34-37ºS showing an important northward deflection at approximately 84ºW. Meanwhile, the SAF can be also identified by surface velocity, EKE and maximum q gradient at 100-400 m depth, showing a geographical position approximately between 55-60ºS. On the other hand, Letelier *et al*. (2009) had shown a slightly seasonal variability in the STF position, revealing a low meridional fluctuation among seasons, and a deflection to NE from 85ºW located from 24º-27ºS.

Mixed Layer Depth (MLD)

Figure 4c shows the spatial distribution of mean MLD off the Chilean coast, showing a shallow MLD in a coastal band (<75ºW) which does not exceed 30 meters, and high depths (>60-70 m) in two different regions associated with sub-tropical oceanic waters at 18-24ºS and westward 85ºW, and sub-antarctic waters southward 45ºS.

Moreover, the seasonal variability of MLD in the SPO shows a strong seasonal cycle with clear differences between summer-autumn and winter-spring. A shallow MLD (<30-40 m) is observed in the summer period, while a strong zonal gradient it is observed in the winter season, which shows a shallow MLD coastal band (<30 m) reaching ~36ºS, contrasting to deeper MLD (>70 m) in the oceanic waters westward 78ºW (Figure 4c). This intense annual fluctuation might be partially linked to the wind annual cycle, which induces a maximum winter turbulent combination when the subtropical anticyclone extension is minimal.

Eddy Kinetic Energy (EKE)

The spatial distribution of mean EKE in the SPO and their seasonal fluctuations are indicated in Figure 4d. The EKE mean field (1992-2005) shows the high mesoscale variability mainly linked to eddies and energetic meandering currents, and exhibits high EKE values (>70 $cm^2 s^{-2}$) between the coast of Chile (until 37ºS) up to 800 km offshore, linked to the intense mesoscale activity that characterizes the Coastal Transition Zone (CTZ, Hormazábal *et al*. 2004). The CTZ presents two coastal conspicuous EKE enhancements, one located off central and southern Perú (~10-18°S) and the second one off central-southern Chile (~25-37°S), separated by a relatively low EKE (<40 $cm^2 s^{-2}$) off northern Chile (~18-25°S). In the deep ocean dynamic zone, another high EKE values core is observed at 34-40ºS and 90-100ºW showing low EKE values compared to CTZ off central Chile (Figure 4d). In these high EKE zones, intensive mesoscale eddies and meanders constitute the dominant structures in the local variability (Hormazábal *et al*. 2004).

Mesoscale eddies have a coherent vertical structure up to ~600 meters depth and generate an offshore transportation of $2x10^6$ $m^3 s^{-1}$ which extends to the rich nutrient waters beyond the zone directly affected by coastal upwelling (Correa-Ramírez *et al*. 2007). Hormazábal *et al*. (2004) pointed out a good spatial association between CHJM fishing sets and enhanced acoustic biomass index with mesoscale eddy edges and strong coastal meandering currents, linked to the high prey availability as a result of physical-biological enrichment processes related to eddy pumping and westward advection of upwelled waters.

The latitudinal distribution of high EKE coastal region located offshore central Chile (CHJM fishing habitat), evidence a moderate seasonal fluctuation, showing a southernmost (northernmost) extension in autumn (spring) season. In contrast, off Peru and northern Chile, and in the oceanic region off central Chile, the EKE seasonal changes are do not evident, although a (less) greater EKE intensity is observed during the autumn(spring) season.

On the other hand, Figure 5 shows the spatial distribution of mean SST, chlorophyll concentration and EKE, and the structure of the CHJM fishery distribution in the SPO. According to the CTZ definition, the spatial pattern of EKE shows some similarities with high and low values of chlorophyll concentration, and with fishing grounds distribution in the oceanic waters off central-southern Chile, suggesting some kind of spatial relationship between CHJM distribution and mesoscale structures (*i e*., eddies and meanders) (Hormazábal *et al*., 2006; Inpesca *unpubl. data*).

Environmental time-series in the Chilean Jack Mackerel habitat

Time-series

The results of the environmental time-series analysis in the CHJM fishing habitat off central-southern Chile are contained in Figure 6. The ENSO index for El Niño 3.4 region shows the alternated warm-cold events (El Niño/La Niña) in the last two decades, emphasizing warm El Niño events in 1987, 1992, 1997-98 and 2003, and the cold La Niña events in 1989, 1999 and 2008 (Figure 6a). The sea level anomaly shows a clear interannual fluctuation in the 1993-2008 period, evidencing negative anomalies in 1993-1996 and 2000-2003, and positive anomalies in 1997-1999 and 2004-2008 (Figure 6b), which is positively correlated with the ENSO index calculated for the El Niño 3.4 region, but with a 9-18 months lag.

The time-series for EKE calculated for CHJM fishing habitat (35-42ºS, coast-90ºW), shows positive anomalies in 1995-2000 (with exception of1998) and in 2006-2008, revealing high EKE values linked to high mesoscale eddies activity and meanders currents. Inversely, a negative anomaly in 2002-2006 period was observed (Figure 6c), revealing a high(low) dynamic of these mesoscale structures in central Chile associated to El Niño(La Niña) events in the tropical Pacific.

The SST anomaly showed an alternate of warm/cold signal in the CHJM fishing habitat. Figure 6d shows warmer periods for 1987-1990 and 1995-1999, and a colder period between 1991 and 1994; however, since 2000 an almost annual warm/cold signal is observed, emphasizing a strong positive anomaly for 2008. In most cases, this reveals that the SST values measured in CHJM fishing habitat seem to be inversely correlated with the ENSO index in the tropical Pacific.

The oceanic chlorophyll concentration for 1997-2008 time-series off central Chile, also showed an interannual fluctuation characterized by positive anomalies in1999-2001 and 2006-2008 revealing a high phytoplanktonic biomass for these periods, and negative anomalies in 2002-2005 (Figure 6e). These anomalies show a a clear missmatch with the tropical ENSO signal, but a high correlation with EKE anomalies, that is, periods of increased production linked to high activity of mesoscale structure in the CHJM fishing habitat off center-southern Chile.

Figures 6f and 6g both show the anomalies of 16ºC isotherm meridional displacement in the 80ºW zonal band, and the meridional fluctuation of the WWD eastern bifurcation zone. This isotherm has been used as a operative southern limit of STF in the SPO (Evseenko 1987, Sepúlveda *et al*. 2003, Cubillos *et al*. 2008), revealing an important meridional fluctuation beyond 80ºW (Sepúlveda *et al*. 2003). Figure 6f shows positive anomalies in 1985-1988, 1991-1995, 1996-1998 and 2000-2005 revealing a southward displacement of 16ºC isotherm from 55-230 km, meanwhile negative anomalies were observed in 1988-1991, 1996, 1999 and 2006-2008, which led to san isotherm displacement of 100-240 km to north. These results shows a ~6-10 months lag with positive(negative) ENSO index in the tropical Pacific.

Finally, Figure 6g shows the meridional fluctuation of the WWD eastern bifurcation zone in center-southern Chile. Positive anomalies indicate a 220-450 km southward displacement, while negative anomalies show a mean displacement of ~300 km northward on several occasions. It should be noted that maximum displacement to south(north) were verified in the 1997-1999 El Niño(La Niña) event.

Meridional and Zonal Hovmöhler Diagrams

The major catches of CHJM take place from 32-45ºS off central-southern Chile. The time–zonal distance plots (Figure 7) shows a strong annual variability, which is observed in SST, chlorophyll concentration and EKE. Because of the coastal upwelling, a lower sea surface temperature and a higher chlorophyll concentration are observed near the coast in December-February. EKE increase offshore during the year produce the seasonal westward propagation of mesoscale eddies and Rossby waves. Additionally, CHJM catches display a seasonal variation, and changes in the location of fishing grounds during the year. In the austral summer fishing sets are located near the coast in northern zone, but fishing grounds gradually shift about 500 km offshore toward the middle of the year (austral winter). However, since 2000 winter catches of CHJM have been carried out beyond 500 km from the coast, reaching 1500 km offshore during 2004-2008. Particularly in 2008, almost all catches were made exclusively in oceanic waters at 600-1000 km from the coast.

In addition, an interannual variability of SST, chlorophyll concentration and EKE it was also observed in the CHJM fishing habitat off central-southern Chile (Figures 8-10), which has been mainly linked to tropical variability associated to El Niño events [Correa *et a*l. 2007]. During the strong warmer and colder 1997-1999 ENSO events, the lowest and highest SST off central-southern Chile, were respectively observed. For the rest of time-series, an inverse correspondence in SST anomalies was noted in central Chile (tropical Pacific) showing high(low) SST during cold(warm) ENSO (Figure 8). In the oceanic region off central Chile (offshore 500 km) six warmer periods were observed (1995-1997, 1999, 2001-2004, 2006 and 2008) in contrast to four colder periods (1998, 2000, 2005 and 2007).

The chlorophyll concentration anomalies also reveal interannual fluctuations in the CHJM fishing habitat (Figure 9), showing three periods of negative anomalies (low values) in 1999, 2002 and 2006, and three periods of high chlorophyll concentration (positive anomalies) in 2000-2001, 2003 and 2008. A zonal difference in the chlorophyll concentration anomaly can be noted when the Coastal Transition Zone (~600 km) and the oceanic dynamic is considered; for instance, in 1998 and 2003 low(high) values were detected in coastal(oceanic) waters and, high(low) chlorophyll concentration was observed for coastal(oceanic) regions in 2004 and in 2005-2007. Figure 9 also indicates an offshore chlorophyll anomalies displacement mainly linked to meso-scale eddies dynamics (Correa *et al*. 2007), which reach beyond the CTZ limit after 6-10 months.

Similarly, the EKE Hovmöhler plot shows an important interannual and zonal variation in the CHJM fishing habitat, evidencing higher EKE values and offshore extension during colder periods linked to the increment of mesoscale eddies activity. Inside the CTZ, an alternate between low/high EKE was observed in 1995-1997 (low values), 1997-2001 (high values), 2002-2005 (low values) and finally in 2006-2007 (high values) (Figure 10), which reveals an interannual variability in the mesoscale eddies activity off central Chile, from the coast to ~600 km offshore. On the contrary, a low variability band of EKE was observed at 600 ~1200 km offshore, which also shows low EKE values in almost the entire period.

During the warmer period in 2002-2006, low values of EKE and SST were observed inside the CTZ off central-southern Chile. This observations were coherent with the initial shift of CHJM fishing grounds shown as a fishing center mass in Figure 10, and it may indicate a link between the low activity of mesoscale structures and fishing distributional pattern. Also, the high values registered in coastal zone for 2006 show an eastward distribution of mass center, but returning westward in 2007-2008 when low EKE were again observed.

This situation might suggest a complex association between the CHJM population dynamics, the effects of fishing and environmental variability, that may explain the spatial distributional pattern of CHJM in the oceanic waters off central-southern Chile during the last decade.

Environmental thresholds

In order to link the CHJM acoustic biomass to physical fluctuations, an analysis of environmental threshold was carried out using information from acoustic cruise performed in the CHJM fishing habitat off central Chile in 2007 (Sepúlveda *et al*. 2009). Results indicate the major acoustic biomass associated to: a) a narrow range of SST (10 to 13ºC, mean= 11.5 ± 1.4 ºC) and surface density (25.0 to 25.25 kg m^{-3}, mean= 24.14 ± 0.12 kg m^{-3}), b) neutral sea level anomaly (-3.5 and 3.5 cm, mean= 0.53 ± 3.4 cm) and vorticity (-1.3 to 1.3 $x10^{-6}$, mean= -7.3 $x10^{-8}$ ± 1.3 $x10^{-6}$), c) moderate geostrophic currents (1.3 to 8.5 cm $s^{-1,}$ mean= 5.2 ± 3.9 cm s^{-1}), and d) a thermocline depth ranged between 35-60 m (mean= 47.8 ± 13.5 m). The sea level anomalies, vorticity and geostrophic currents ranges observed, are typical values for regions dominated by mesoscale eddies and meanders currents (Hormazábal *et al*. 2004, Correa *et al*., 2007).

CONCLUDING REMARKS

The results contained in this paper were obtained from physical and fisheries observations in the oceanic habitat of Chilean Jack Mackerel off central-southern Chile and lead to the following concluding remarks :

- The major fishing CHJM habitat is a region characterized by important environmental gradients observed in the SST, SSS and MLD, but it is also affected by the upwelling system off central-southern Chile. In this region, a high meso-scale activity seems to determine the oceanic biological productivity and a possible link with CHJM schools distribution.

- The CHJM habitat has undergone an important inter-annual variability in the last three decades, which is mainly associated to tropical perturbations such as El Niño/La Niña. SST in CHJM habitat seems to be in opposite phase to the tropical signal, and the EKE interannual variability seems to control the interannual productivity fluctuations in oceanic waters off central Chile.

There is lack of information as to the manner in which the sub-antarctic fluctuations can influence the climatic-oceanographic variability and CHJM habitat off central Chile.

Our results suggest a complex association between CHJM biomass and the environmental variability at the interannual scale for the study region, mainly linked to tropical climatic-oceanographic indexes. However, the study should also consider the population dynamics, fishing effort and migrations to clarify and strengthen the associations between Chilean jack mackerel and the environmental dynamics in the Southeastern Pacific Ocean.

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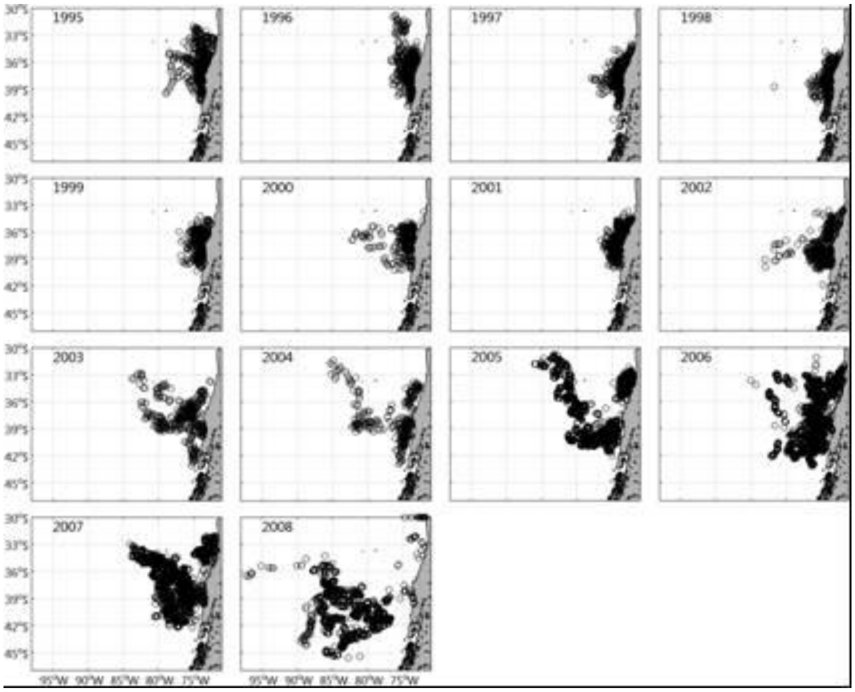

Figure 1. Inter-annual variability of the position of the Chilean Jack Mackerel (CHJM) fishing grounds in oceanic waters off central Chile, obtained from the logbook fishing data.

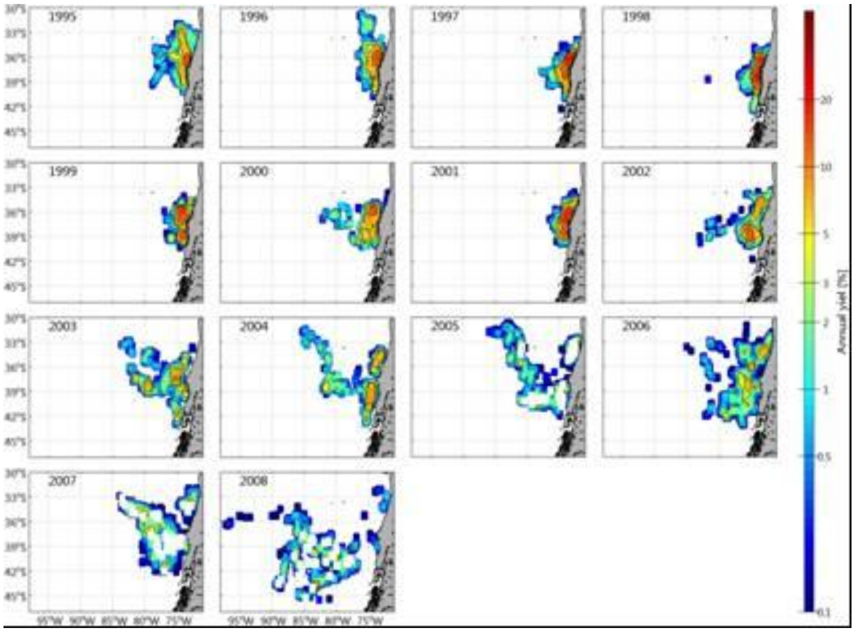

Figure 2. Inter-annual variability of the spatial CHJM annual catches (%) in the oceanic waters off central Chile.

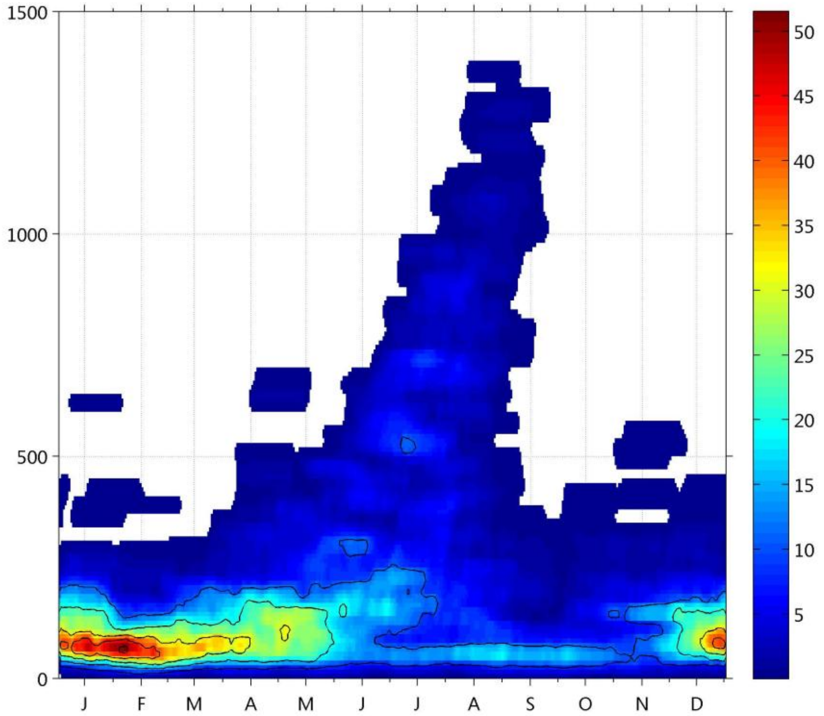

Figure 3. Climatology of CHJM catches (tons) in oceanic waters off central Chile from 1995 to 2008.

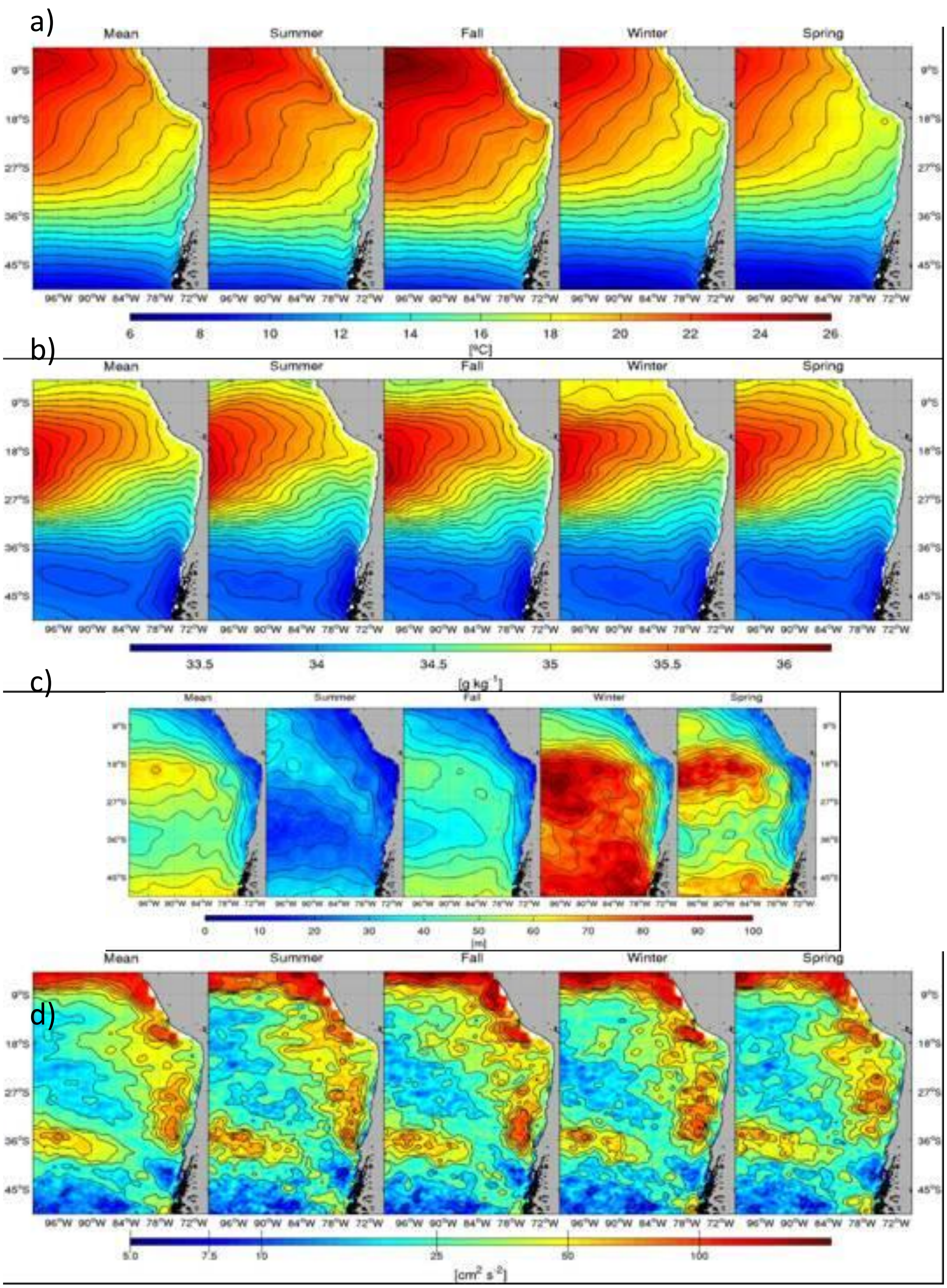

Figure 4. Spatial average distribution of a) Sea surface temperature (ºC), b) Sea surface salinity (g kg^{-1}), c) Mixed layer depth (m), and d) Eddy kinetic energy (cm^2 s^{-2}) in the Southeastern Pacific Ocean. Figures a, b, c consider 1975-2005, and Figure d considers 1997-2005 period.

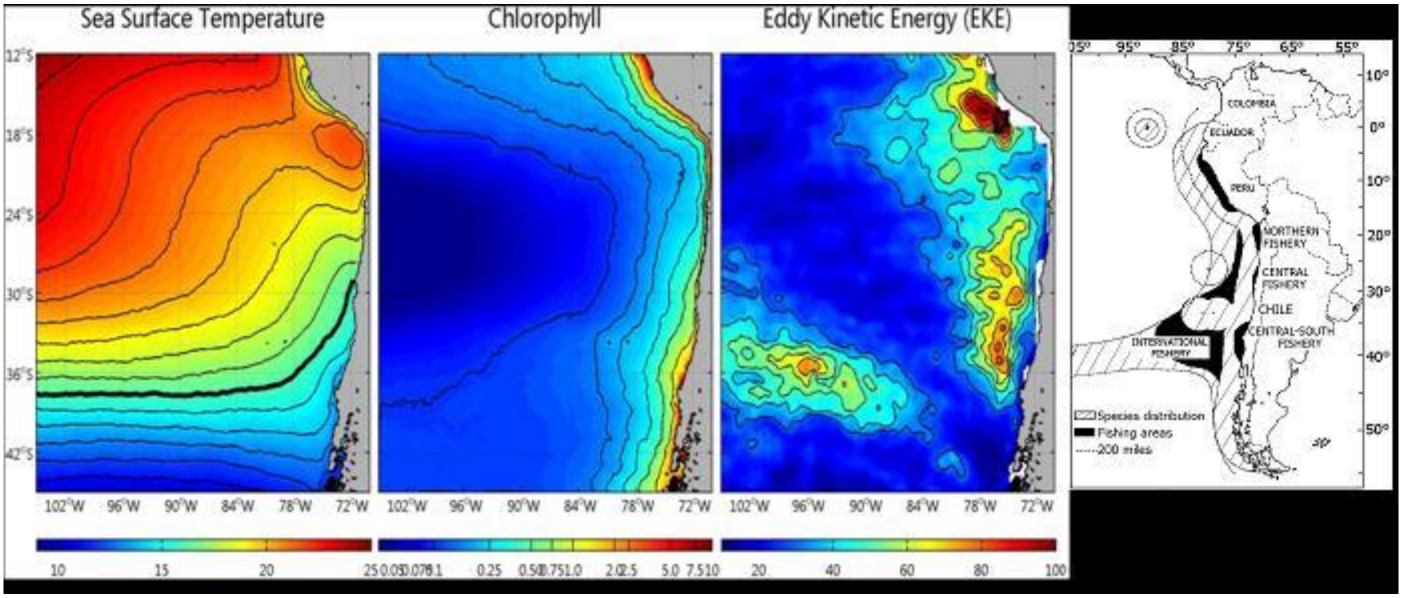

Figure 5. Spatial average distribution of a) SST (1985-2008, ºC), b) chlorophyll (1999-2008, mg m^{-3}), c) eddy kinetic energy (1997-2008, cm^{2} s^{-2}), and d) schematic representation of CHJM fishing regions in the Southeastern Pacific Ocean.

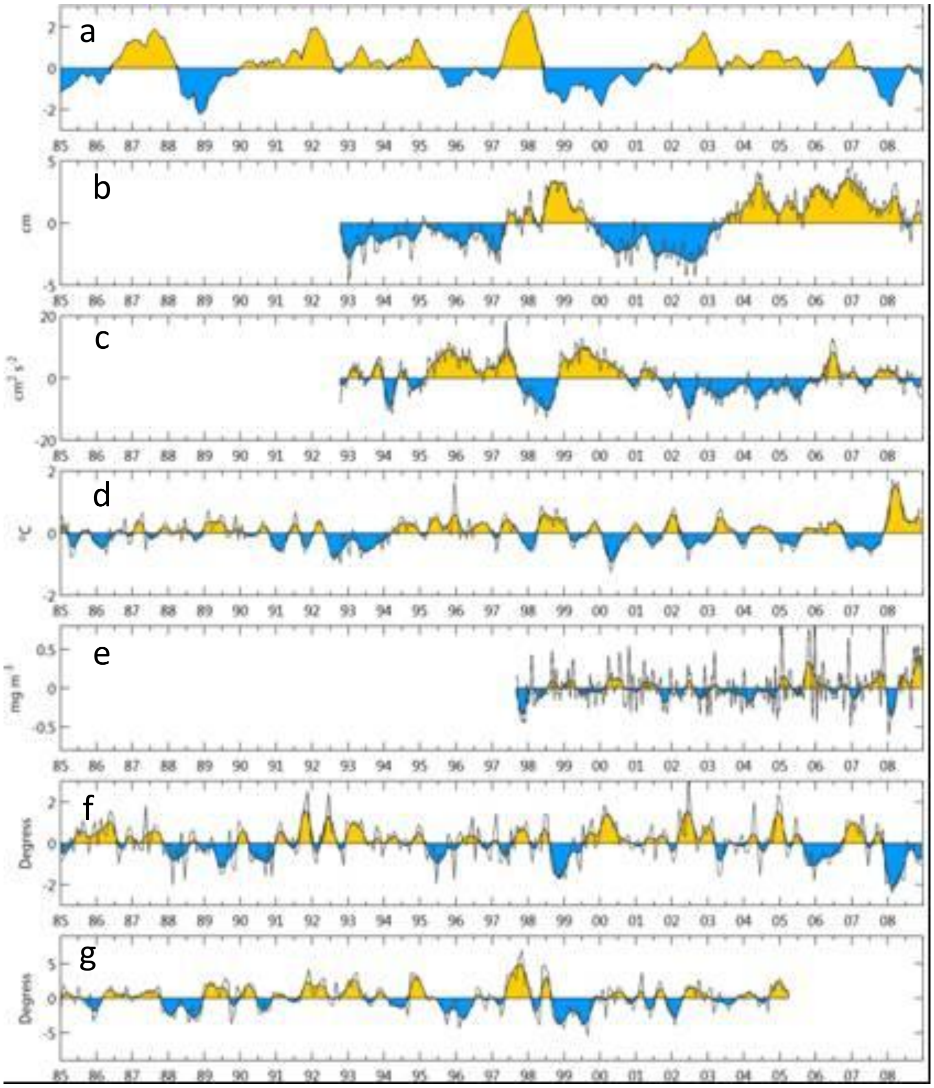

Figure 6. Time-series of environmental indexes in the SPO. a) ENSO index, b) sea level anomaly, (m) c) Eddy kinetic energy anomaly (cm^2 s^{-2}), d) SST anomaly (ºC), e) surface chlorophyll anomaly (mg m^{-3}), f) latitudinal anomaly of 16ºC isotherm at 80ºW (latitudinal degrees), and e) latitudinal anomaly of geographical position of WWD bifurcation zone (latitudinal degrees).

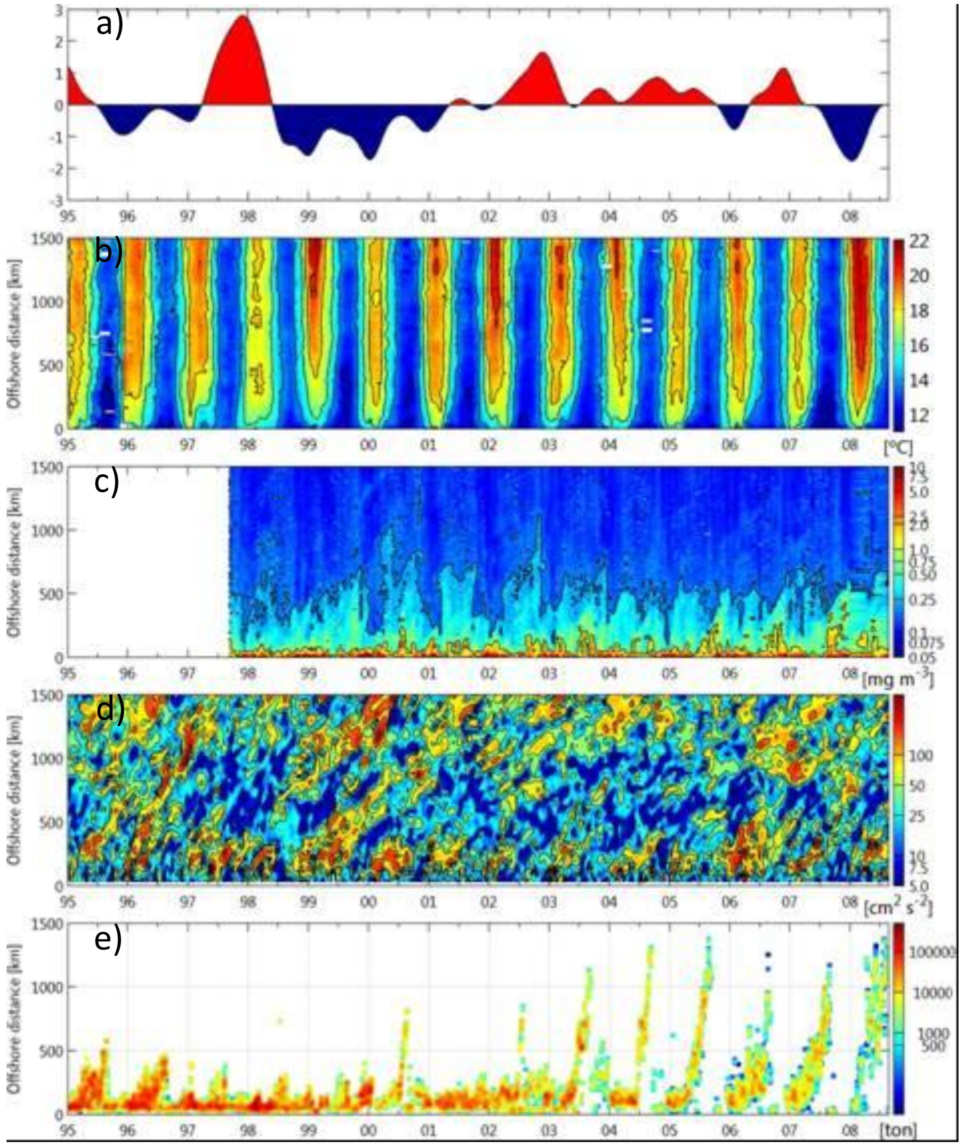

Figure 7. Hovmöhler time-zonal distribution of environmental variables considering the 38ºS band. a) ENSO index, b) SST (ºC), c) Chlorophyll concentration (mg m^{-3}), d) Eddy kinetic energy (cm^2 s^{-2}), and e) CHJM catches (tons).

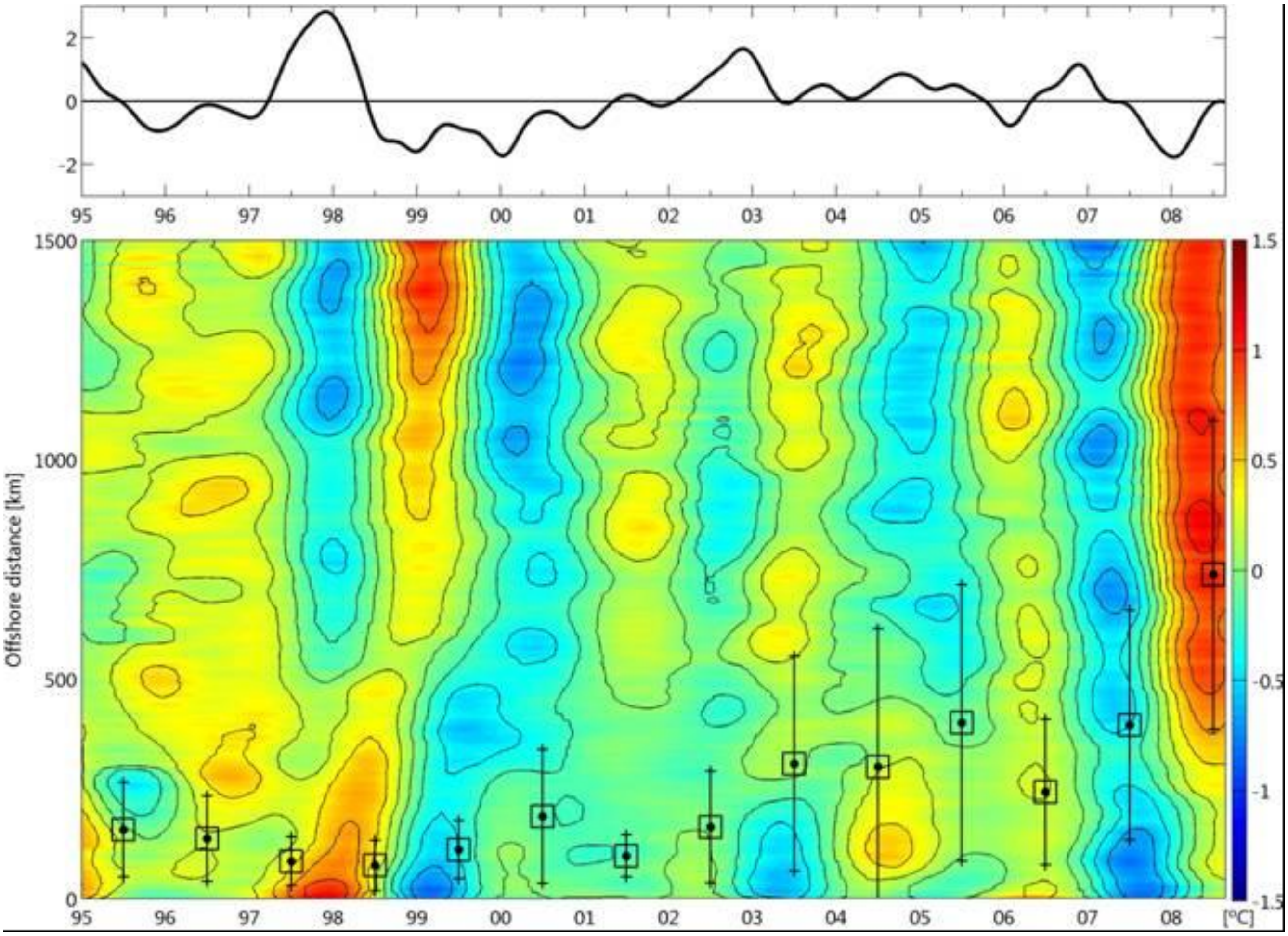

Figure 8. Hovmöhler time- zonal plot of SST anomalies (ºC) in the CHJM habitat off central-southern Chile, considering the 39ºS band. Boxes represent the CHJM mass centers for 1995-2008. Time-series of ENSO index variability are also included.

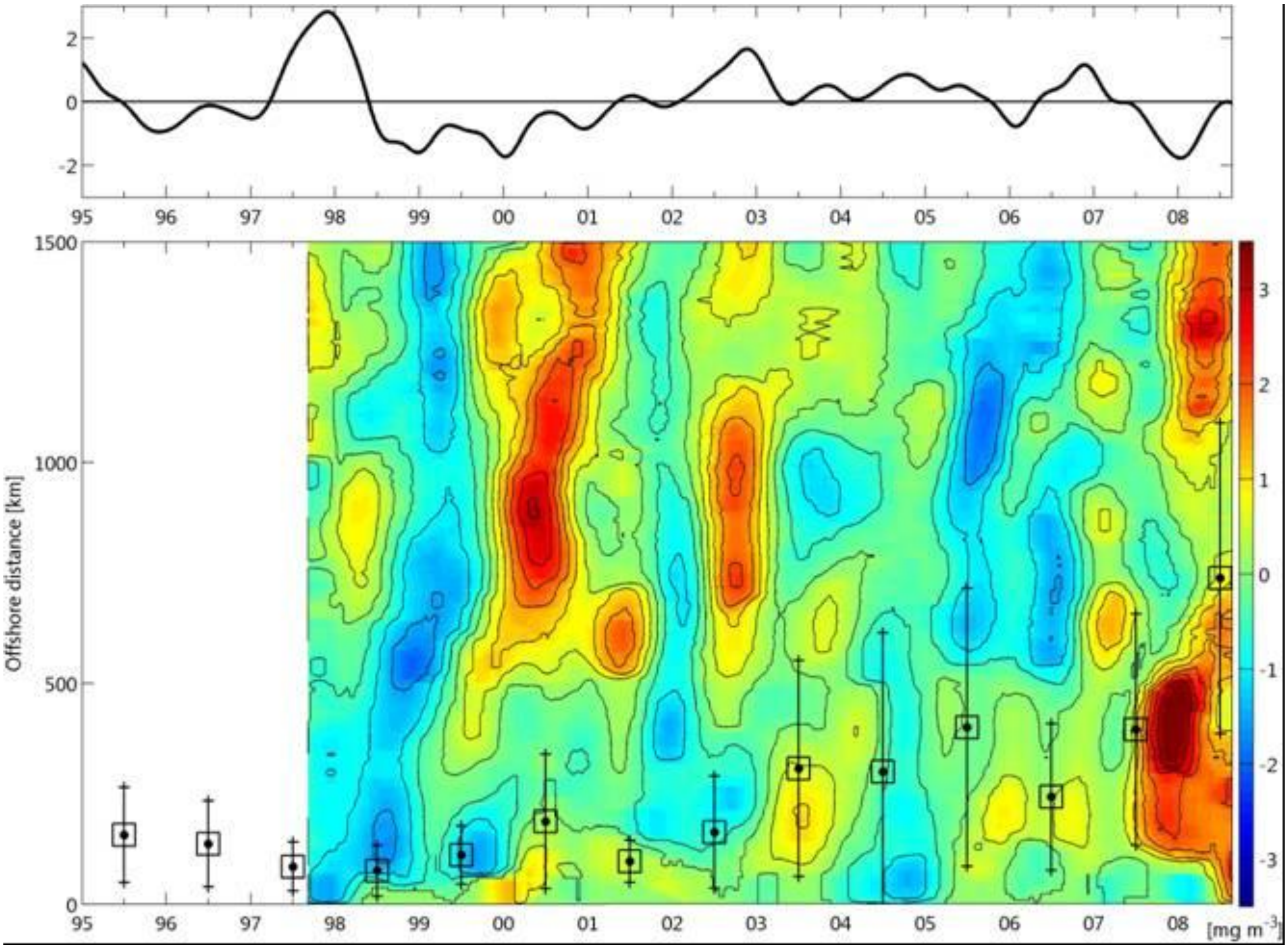

Figure 9. Hovmöhler time- zonal plot of surface chlorophyll anomalies (mg m^{-3}) in the CHJM habitat off central-southern Chile, considering the 39ºS band. Boxes represent the CHJM mass centers for 1995-2008. Time-series of ENSO index variability are also included.

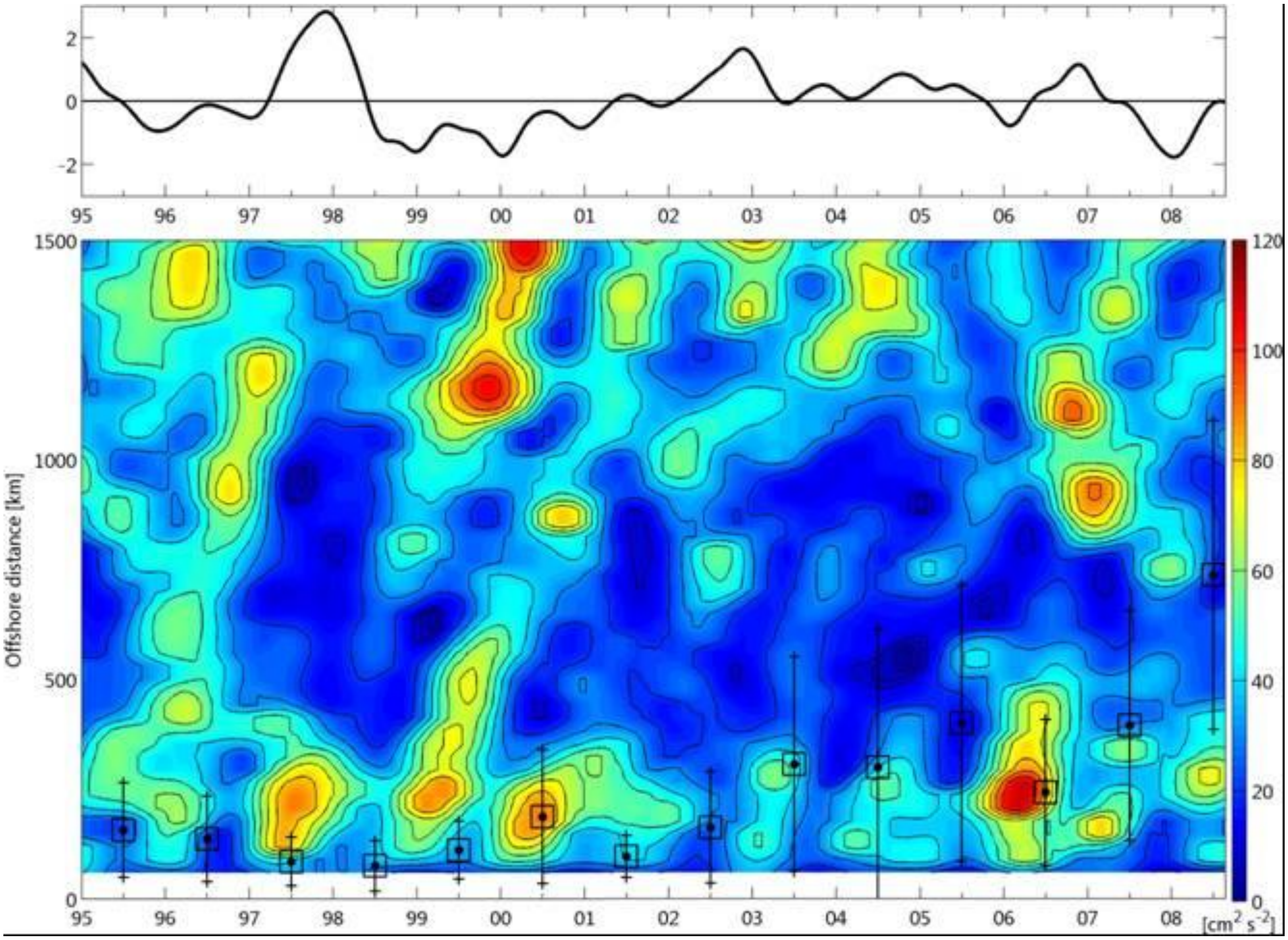

Figure 10. Hovmöhler time- zonal plot of eddy kinetic energy (cm^2 s^{-2}) in the CHJM habitat off central-southern Chile, considering the 39ºS band. Boxes represent the CHJM mass centers for 1995-2008. Time-series of ENSO index variability are also included.

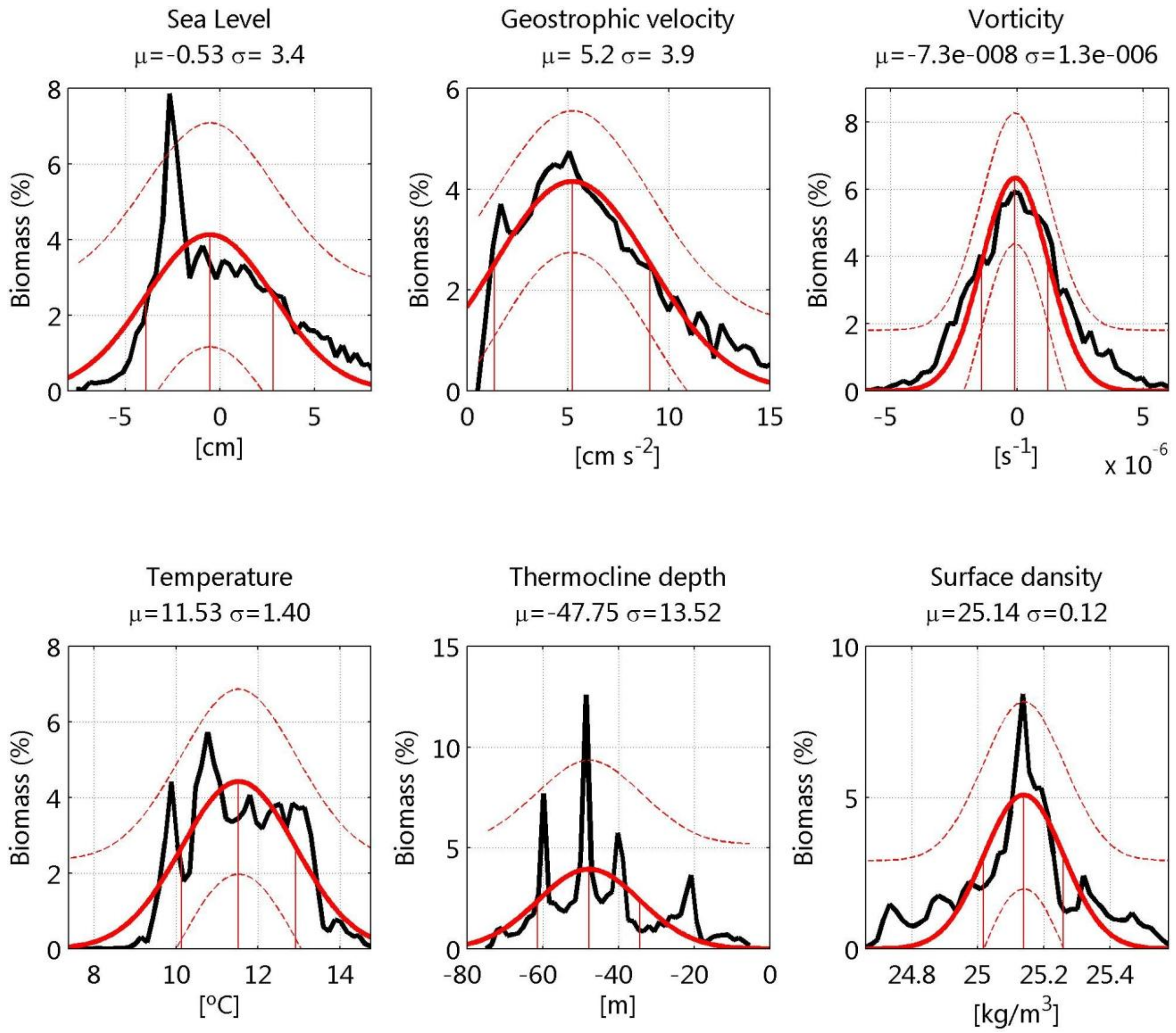

Figure 11. Environmental range in the CHJM habitat off central-southern Chile and acoustic biomass distribution. Red line represent the Gaussian function fitted, vertical red lines the average and ± 1 standard deviation, and dashed lines the 99.5% confidence intervals.