7th MEETING OF THE SCIENTIFIC COMMITTEE

La Havana, Cuba, 7 to 12 October 2019

SC7-HM03

Spatio-temporal distribution pattern of jack mackerel off South-central Chile

Chile

Spatio-temporal distribution pattern of Chilean jack mackerel (*Trachurus murphyi*) fishing grounds and environmental variability off southern-central Chile

Sebastián Vásquez[1], Aquiles Sepúlveda[1] & Sergio Nuñez[1]

Abstract

The Chilean jack mackerel displays a wide spatial distribution in the Southeast Pacific, extending from the coast line of South America to New Zealand and Tasmania. Within this broad distribution, this species supports an important fishery that reaches its maximum catch levels off southern-central Chile where both the Chilean purse-seine industrial fleet and the international fleet operate. From statistical fishing data of the Chilean industrial fleet, the spatio-temporal variability of the Chilean jack mackerel fishing grounds in the 1995-2019 period was described. For the same region, environmental variability was analyzed using satellite information. The spatio-temporal distribution of Chilean jack mackerel catches revealed marked differences in the seasonal pattern of catches and in the offshore extension of the purse-seine fleet. According to the above, three periods were identified: i) 1995-2001 characterized by catches throughout the year, an offshore extension during July and August that did not exceed 900 km and an average annual catch of 2, 1 million tons; ii) 2002-2011, with catches throughout the year, mostly in the first half and a large offshore extension of the fleet from March to August reaching up to 1800 kilometers offshore and an average annual catch of around 900 thousand tons, and finally; iii) 2012-2019 characterized by concentrated catches in the first half, absence of fishing activity between September and November, with an offshore extension that did not exceed 600 km and average catches around 290 thousand tons. The environmental variability revealed a highly dynamic habitat influenced by El Niño/La Niña events, and characterized by strong spatial gradients mainly associated with a coastal zone of highly productive upwelling, seasonal migration of the Pacific anticyclone and the presence of coastal transition zone with strong mesoscale activity. Interannually, a period of negative anomalies in the sea level height and primary production and positive in sea surface temperature between 1995 and 2002, followed by a period of neutral activity between 2003 and 2013, and a period of positive anomalies of the sea level height, low kinetic activity and higher productivity between 2014 and 2019.

1. Introduction

Chilean jack mackerel (CHJM; *Trachurus murphyi*, Nichols) from the southern Pacific constitutes one of the most important pelagic fisheries in the world. Over the last 16 years, total landings have declined from a maximum of 4.4 million tons in 1994 to a minimum of 353,000 tons in 2013, after which, a slight increase has been observed to reach 531,000 tons in 2018 (Figure 1). Chilean fishery authorities set a minimum legal size of 26 cm in 1982, closed the fishery to new boats in 1990, set an annual quota in 1999, and imposed a total allowable catch per vessel in 2003 (Figure 1). The South Pacific Regional Fisheries Management Organization (SPRFMO) is an inter-governmental group committed to the long-term conservation and sustainable use of fishery resources in the South Pacific Ocean (https://www.sprfmo. int/). The SPRFMO Convention has applied to the high seas of the South Pacific since 2009. Jack mackerel is one of the commercial resources managed by the SPRFMO, which is composed of countries with fishing interests in the South Pacific jack mackerel fishery.

CHJM is a highly migratory, pelagic species that is widely distributed in the ESP off Chile and Peru, reaching across to New Zealand and Tasmania (Bailey, 1989; Serra, 1991; Elizarov et al., 1993; Arcos & Gretchina, 1994; Suda et al., 1995; Gretchina, 1998; Arcos et al., 2001). The wide distribution of this species in the region and its highly migratory behaviour make it difficult to gather evidence supporting specific hypotheses about its spatial dynamics and population structure. However, it is recognized that CHJM 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 extend along the southeaster Pacific Ocean (SPO), but mainly in oceanic waters off central Chile from the 82°W to beyond 90°W (Cubillos *et al*. 2008; Núñez *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, being more available for the Chilean purse-seiner fleet (Arancibia *et al*. 1995). Spawning occurs mainly between October and December, although it can extend from September to February (Grechina et al. 1998). In this context, CHJM exploits a wide range of environmental conditions since it occupies highly heterogeneous regions in terms of oceanographic and prey conditions (Bertrand et al., 2006; Alegre et al., 2015).

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 Kelvin waves, coastal trapped waves and Rossby waves (Strub et al. 1998), and decadal variability (Klyashtorin 1998). 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). Despite this environmental variability, a suitable CHJM habitat has been proposed, which is strongly related with thermal and productivity conditions associated with the presence of the subtropical front, which extends from the oceanic region in front of south-central Chile to the coasts of north-central Chile, Peru and Ecuador (Bertrand et al., 2016, Vasquez *et al*., 2013). However, within this broad and spatially continuous suitable habitat, it is suggested that specific changes in the spatial-temporal pattern of CHJM may occur in response to different population sizes or local environmental conditions (Gretchina et al., 2016).

In this context, the objective of this contribution is to describe the variability of the spatio-temporal distribution pattern of jack mackerel fishing areas off central-southern Chile, where historically the greatest catches have been reported, and to describe the environmental variability of this region in the period 1995-2019. Owning the high seasonal and interannual variability of environmental conditions in the study area, we focus both on interannual and intra-annual patterns of variability.

2. Methods

2.1. Fishery data

Chilean jack mackerel spatial information were obtained from historical catch data collected by Instituto de Fomento Pesquero (IFOP) and Instituto de Investigación Pesquera (INPESCA), which through a joint work generated a single database of georeferenced catches from 1995 to 2019, which increased the number of records and eliminated those that were duplicated. Thus, for determining the fishing area locations and CHJM catches, three different data sources were used: fishing set statistics obtained from fishing logbook for each vessel, the geographical position of each vessel reported 2 times daily, the landings (in tonns) and the onboard observer reports. The total database consisted of 29,351 spatially referenced fishing sets associated with the catch weight. In order to describe, the spatial pattern of CHJM, the catch data on each fishing ground was re-sampled by using a 10 x 10 km regular square.

2.2. Environmental data

On the basis of their spatio-temporal availability, local and global relevance according to previous work and contribution to preliminary analyses. Unfortunately the availability of biotic and abiotic data on the horizontal and vertical planes over the CHJM distribution range is scarce. As a consequence satellite environmental data (Table 1) were used in order to describe CHJM habitat variability off central-southern Chile: sea surface temperature (SST, in ºC), sea surface chlorophyll-a concentration (CHL-a, in mg m^{-3}) as a *proxy* of primary production, sea level anomaly (in cm), eddy kinetic energy (EKE, in cm^2 s^{-2}) as a *proxy* of mesoscale activity and wind induced turbulence (WIT, in m^3 s^{-3}) as a proxy of water column stability.

2.3. Statistical analyses

3. Results

3.1. Spatio-temporal variability of CHJM fishing grounds

The interannual variability of the spatial distribution of the purse-seine fleet oriented to Chilean jack mackerel catches and its annual landing levels is shown in Figure 2. This spatio-temporal pattern revealed three periods with different spatial configurations:

i) period 1995-2002: in our study area, this period corresponds to an Olympic Race (OR) regime, with incentives to maximize catch volume per trip in the shortest possible time which promoted high landing levels, with a maximum peak in 1995 with 3.8 million tons. Regardless of the prevalence of restricted entry regulations, the absence of fishing quotas (global and individual) and the risk of fishing closure prompted this behavior (see Figure 1). Despite these high landing levels, the spatial distribution of the catch revealed high levels of jack mackerel availability within the exclusive economic zone of Chile, with over 50% of the records in the coastal region (> 75ºW), with high yields per unit area (Figure 2). Seasonally, this period was characterized by catches throughout the year with an offshore extension during July and August that did not exceed 900 km (Figure 3a). The above suggests a high carrying capacity of the coastal system off central-southern Chile to support these high biomass, considering that fishing activity mostly occurs during the CHJM feeding period.

ii) period 2003-2011: This period was characterized by a marked decline in landings (1.3 million tons in 2003) and corresponds to the beginning of the regulation through maximum catch quotas per vessel owner and with the increase in the activity of the international fleet outside Chile's juridical waters (see Figure 1). This scheme started in February 2001 and distributed percentage-shares upon the annual total allowable quota (TAC) to vessels with valid fishing permits for this fishery. Per vessel TAC shares were initially allocated by weighting historical catch and fishing capacity records per vessel. Under this scenario of lower landings and new administrative regulation, catches still occurred throughout the year, mostly in the first half and a large offshore extension of the fleet from March to August. At the same time, jack mackerel availability decreased in the coastal region of central-southern Chile, encouraging an offshore displacement of the fleet, reaching beyond

1800 km of offshore extension in 2009, with low yields per unit area (Figure 2). Seasonally, this period was characterized by catches throughout the year with an offshore extension during July and August that did not exceed 900 km (Figure 3b).

iii) period 2012-2013: This period is characterized by a stability of landings under low population sizes, with a slight increase in recent years, in response to increases in recruitment strength. From an administrative point of view, this period coincides with the formalization of the South Pacific Regional Fisheries Management Organization (SPRFMO), an inter-governmental group committed to the long-term conservation and sustainable use of fishery resources in the South Pacific Ocean (Figure 1). The SPRFMO is responsible for the integrated fishing management of jack mackerel since 2001 and set the maximum global catch quotas for the entire southern Pacific. In this recent scenario, the yield per unit area in jack mackerel catches has increased in the central-southern region of Chile, and fishing activity has not extended beyond 600 km offshore (Figure 2). In addition, seasonally catches have been concentrated between December and April, mostly in the coastal region (<250 km offshore) and with a season without fishing more extensive than the previous periods (September-November) (Figure 3c). In 2019, this scenario has been consolidated, with very concentrated catches near the main landing ports, fishing areas that did not exceed 200 km offshore and high yields per unit area. The above has promoted a 90% compliance of the fishing quota during the first semester.

3.2. Environmental variability

In consideration of the spatio-temporal changes of fishing areas pattern, as a *proxy* for the jack mackerel spatial distribution, one of the open questions is what is the role of habitat conditions in the displacement of mass centers of jack mackerel population in the southeastern Pacific. In order to analyze the seasonal and interannual variability in the habitat conditions of CHJM, an approach based on satellite information was used.

The sea surface temperature shows a marked seasonality in the southern-central region off Chile, which is related to changes in solar radiation and the seasonal movement of the subtropical front in its summer migration towards the pole (Figure 4b). The amplitude of the seasonal signal seems to be related to the variability of the equatorial signal of the El Niño index, which shows alternating patterns throughout the study period promoting dominance of warm and cold periods (Figure 4a). 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 during 1987, 1992, 1997-98, 2003 and 2015-2016, and also the cold La Niña events during 1989, 1999 and 2008.

Because the coastal upwelling, a lower sea surface temperature and a higher chlorophyll concentration are observed near the coast during December-February (Figure 4b). These centers of high biological productivity are extended offshore as a result of intense mesoscale activity in the coastal transition zone, promoting maximum winter chlorophyll concentration in the oceanic region, where the persistence of meso-scale eddies traveling northwestward, promotes strong gradients of kinetic energy (Figure 4c). As described above, CHJM fishing grounds shows a seasonal variation that include fishing activity near the coast during austral summer and a gradual offshore displacement to reach its maximum expansion during austral winter (Figure 4d). The sea level anomaly shows a clear interannual fluctuation in the 1993-2019 period, evidencing negative anomalies during 1993-1996 and 2000-2003, and positive anomalies for 1997-1999 and particularly for 2014-2019 (Figure 5b), which is positively correlated with the ENSO index calculated for the El Niño 3.4 region with 9-18 months lag. The time-series for EKE in CHJM fishing habitat revealed positive anomalies during 1995-2000 (excepting 1998) and 2006-2008 and a marked period of negative anomalies since 2016, revealing high EKE periods linked to high mesoscale eddies and meanders activity (Figura 5c), 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 5d shows warmer periods for 1995-1999, and colder period between 1991 and 1994; from 2000 to 2014 a neutral situation with a predominance of negative anomalies was observed. From 2015 positive anomalies were observed associated to a strong possitive signal of ENSO index in the tropical Pacific. The oceanic chlorophyll concentration for 1997-2019 time-series off central Chile, also showed an interannual fluctuation characterized by negative anomalies during 1997-2003, followed by a neutral period between 2004 y 2011, a marked positive period between 2011 and 2016 and negative anomalies from 2017 until 2019 (Figure 5e).

Figures 6 to 8 show the interannual zonal variability of the environmental conditions and the location of the centers of mass of the mackerel fishing areas. These analyzes reveal a low correspondence between habitat variations and changes in jack mackerel fishing areas, suggesting a high plasticity of the species against environmental changes. However, more detailed studies regarding the mechanisms behind this spatial dynamics are required.

4. Discussion

5. References

Alegre, A., Bertrand, A., Espino, M., Espinoza, P., Dioses, T., Ñiquen, M., Navarro, I., Simier, M., Ménard, F., 2015. Diet diversity of jack and chub mackerels and ecosystem changes in the northern Humboldt Current system: a long-term study. Progress in Oceanography 137, 299–313. http://dx.doi.org/10.1016/j. pocean.2015.07.010.

Arancibia, H., Cubillos, L., Arcos, D., Grechina, A., Vilugrón, L., 1995. The fishery of horse mackerel *Trachurus symmetricus murphyi* in the South Pacific Ocean. With emphasis on the fishery unitoff Central Chile. Scientia Marina. 59(2): 113 117.

Arcos, D. A., Cubillos, L. A., and Nuñez, S. P. 2001. The jack mackerel fishery and El Ni~no 1997–98 effects off Chile. Progress in Oceanography 49: 597–617.

Arcos, D.F. and Gretchina, A (eds.), 1994. Biología y pesca comercial del jurel en el Pacífico Sur. Editorial Anibal Pinto, Concepción, Chile, 203 p.

Bailey, K. 1989. Description and surface distribution of juvenile Peruvian jack mackerel, *Trachurus murphyi*, Nichols from the Subtropical Convergence Zone of Central South Pacific. Fishery Bulletin US 87: 273–278.

Bertrand, A., Barbieri, M., Gerlotto, F., Leiva, F., Córdova, J., 2006. Determinism and plasticity of fish schooling behaviour as exemplified by the South Pacific jack mackerel *Trachurus murphyi*. Marine Ecology Progress Series 311, 145–156.

Cubillos, L. A., Paramo, J., Ruiz, P., Nuñez, S., and Sepúlveda, A. 2008. The spatial structure of the oceanic spawning of jack mackerel (*Trachurus murphyi*) off central Chile (1998–2001). Fisheries Research 90: 261–270.

Escribano, R., G. Daneri, L. Farías, V. A. Gallardo, H.E. González, D. Gutierrez, C. Lange, C. E.Morales, O. Pizarro, O. Ulloa & M. Braun. 2004. Biological and chemical consequences of the 1997–1998 El Niño in the Chilean coastal upwelling system: a synthesis. Deep-Sea Research II 51

Hormazábal S., S. Núñez, D. Arcos, F. Espíndola & G. Yuras. 2004. Mesoscale eddies and pelagic fishery off central Chile (33-40°S). Remote Sensing of Oceans, Coasts and the Atmosphere: Developments and Applications. Pan Ocean Remote Sensing Conference, 2004. University of Concepción, Nov. 29 – Dec. 03, 2004. Concepción-Chile.

Hormazábal, S., G. Shaffer, J. Letelier & O. Ulloa. 2001. Local and remote forcing of sea surface temperature in the coastal upwelling system off Chile. Journal of Geophysical Research, 106, 16657-16672.

Klyashtorin, L. 1998. Long-term climate change and main commercial fish production in the Atlantic and Pacific. Fish. Res. 37:115-125.

Leth, O. & G. Shaffer. 2001. A Numerical Study of the Seasonal Variability in the Circulation off Central Chile.J. Geophysical Res,vol. 106, no. C10, 22,229 – 22,248, October

Nakata, H., S. Kimura, Y. Okazaki & A. Kasai. 2000. Implications of meso-scale eddies caused by frontal disturbances of the Kuroshio Current for anchovy recruitment. ICES J. Mar. Sci. 57: 143-152.

Núñez, S, S Vásquez, P Ruiz and A Sepúlveda. 2008. Distribution of early developmental stages of jack mackerel in the Southeastern Pacific Ocean. Paper presented to the SPRFMO Chilean Jack Mackerel Workshop, Santiago, 30 June – 4 July 2008.

Rutllant, J. & V. Montecino, 2002. Multiscale upwelling forcing cycles and biological response off north-central Chile. Revista Chilena de Historia Natural. 75:217-231.

Serra, R. 1991. Important life history aspects of the Chilean jack mackerel, *Trachurus symmetricus murphyi*. Investigaciones Pesqueras Chile 36: 67–83.

Strub, P.T., J.M. Mesías, V. Montecino, J. Rutland & S. Salinas. 1998. Coastal ocean circulation off western South America. In: The Sea A.R. Robinson & K.H. Brink (eds). Vol. 11, p: 273-313.

Strub, P.T., J.M. Mesías, V. Montecino, J. Rutland & S. Salinas. 1998. Coastal ocean circulation off western South America. In: The Sea A.R. Robinson & K.H. Brink (eds). Vol. 11, p: 273-313.

Suda, Y., Machii, T., and Orrego, H. 1995. Some fishery and biological aspects of jack mackerels, genus *Trachurus* (Carangidae). Scientia Marina 59: 571–580.

Vásquez, S., Correa-Ramírez, M., Parada, C., and Sepúlveda, A. 2013. Influence of oceanographic processes on jack mackerel (*Trachurus murphyi*) larval distribution and population structure off Chile. ICES Journal of Marine Sciences 70: 1097–1107.

6. Tables

Table 1. Satellite data used for describe Chilean jack mackerel habitat off central-southern Chile.

Parameter	Sensor	Temporal resolution	Spatial resolution	Period	Data source
SST	Pathfinder	Monthly	9 km	1995 Jan-2008 Dec	https://www.ncdc.noaa.gov
SST	MODIS-Aqua	Monthly	4 km	2009 Jan-2019 Jul	https://oceancolor.gsfc.nasa.gov/
CHL-a	Copernicus	Monthly	4 km	1997 Sep-2019 Jul	https://www.copernicus.eu/
Sea level anomaly	AVISO	Daily	1/4 deg	1995 Jan-2019 Jul	https://www.aviso.altimetry.fr/
Geostrophic velocity	AVISO	Daily	1/4 deg	1995 Jan-2019 Jul	https://www.aviso.altimetry.fr/
Wind velocity	CCMP	Monthly	1/4 deg	1995 Jan-2019 Jul	http://www.remss.com

7. Figures

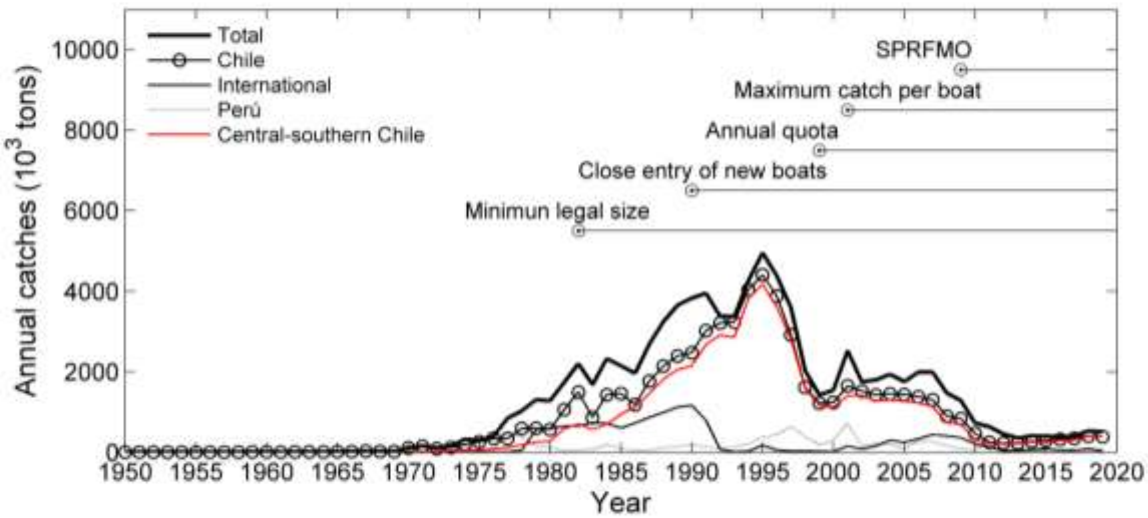

Figure 1. Annual jack mackerel catches carried out by Chilean, Peruvian, and international fleets (database of the Servicio Nacional de Pesca of Chile, Instituto de Investigación Pesquera, and the Food and Agriculture Organization), and the historical Chilean fishery management regulations and bans implemented since 1982. Red line corresponds to the catches of the purse-seine fleet of the central-southern Chile.

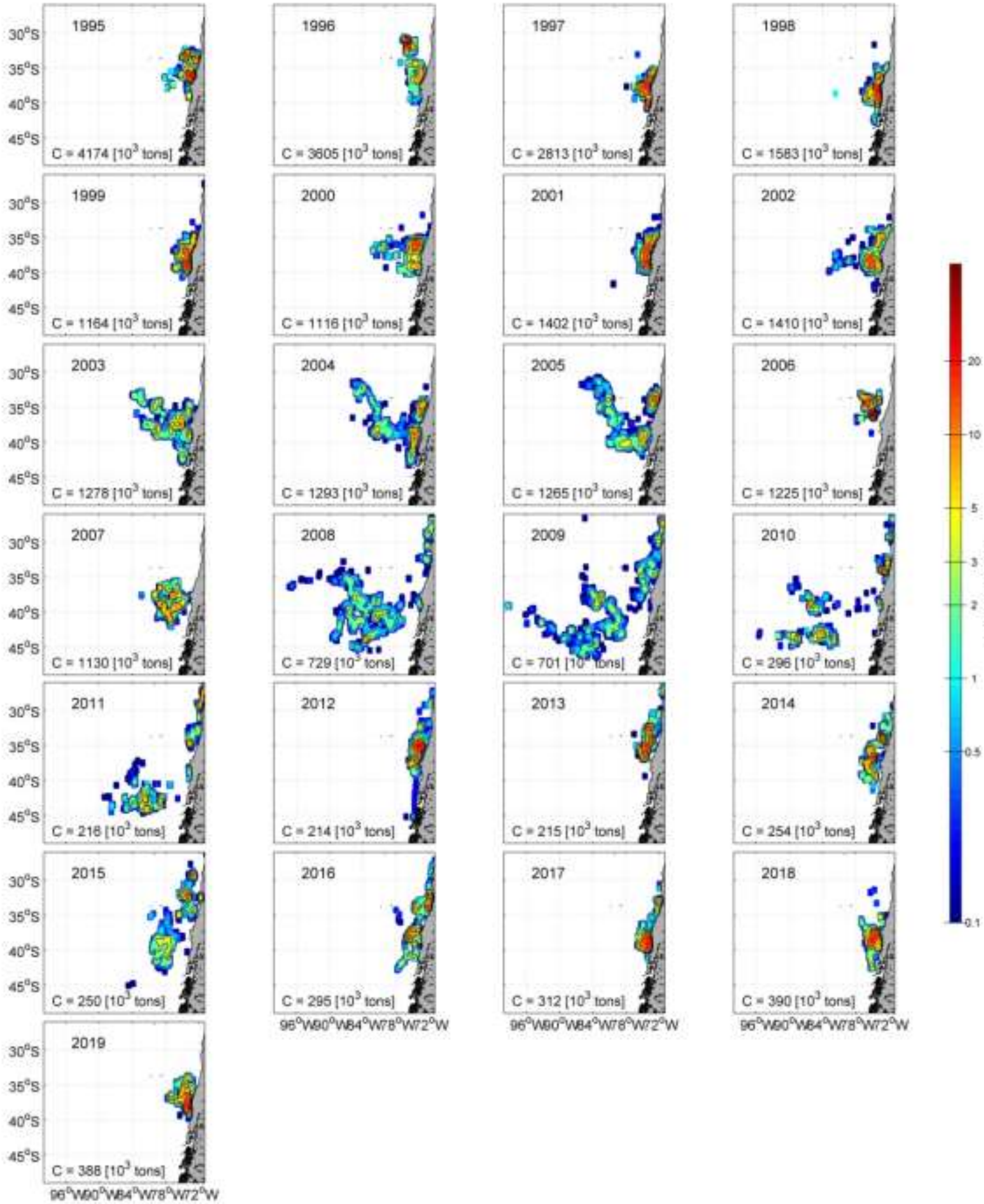

Figure 2. Spatio-temporal variability of Chilean jack mackerel annual catches (%) in cetral-southern Chile, period 1995-2019. The total annual catch of the central-southern Chile fleet is indicated in each panel.

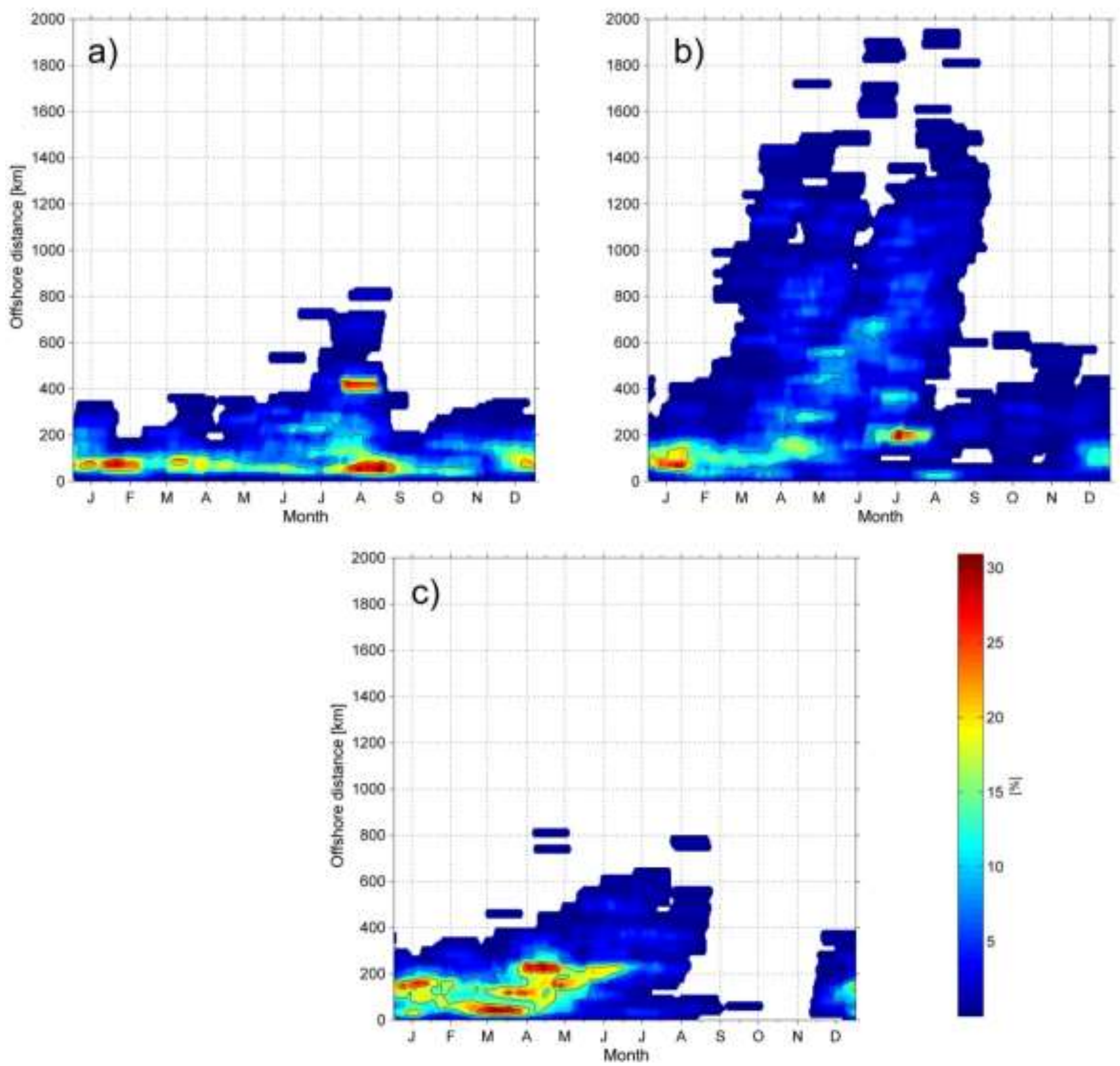

Figure 3. Climatology of the offshore extension of Chilean jack mackerel catches in the central south zone of Chile for the periods: a) 1995-2001; b) 2002-2011 and c) 2012-2019.

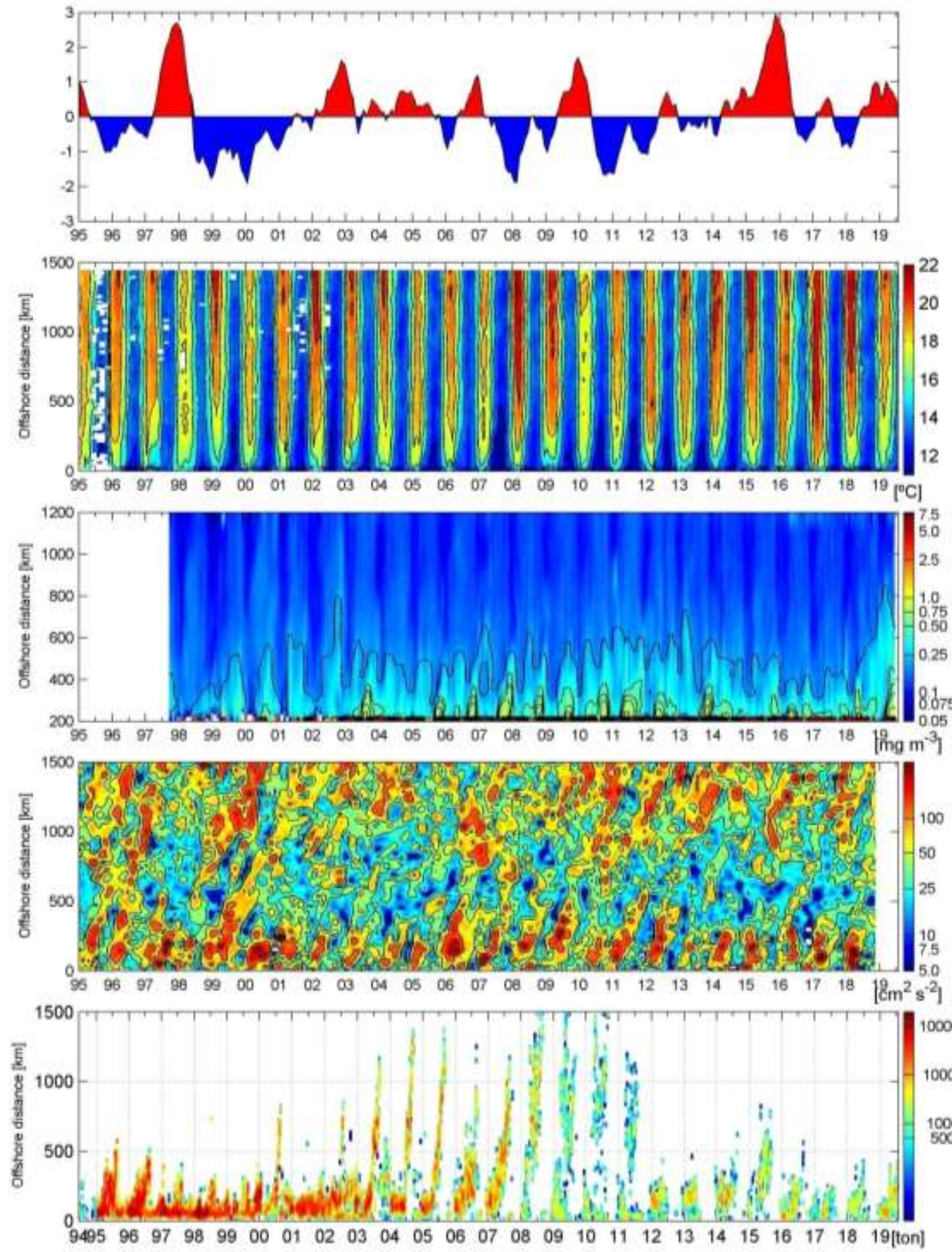

Figure 4. Space-time Hovmöller diagram for Chilean jack mackerel catches and environmental variables considering the 38ºS band. a) region 3-4 ENSO index, b) sea surface temperature (ºC), c) chlorophyll concentration (mg m-3), d) Eddy kinetic energy (cm2 s-2), and e) Chilean jack mackerel catches (tons).

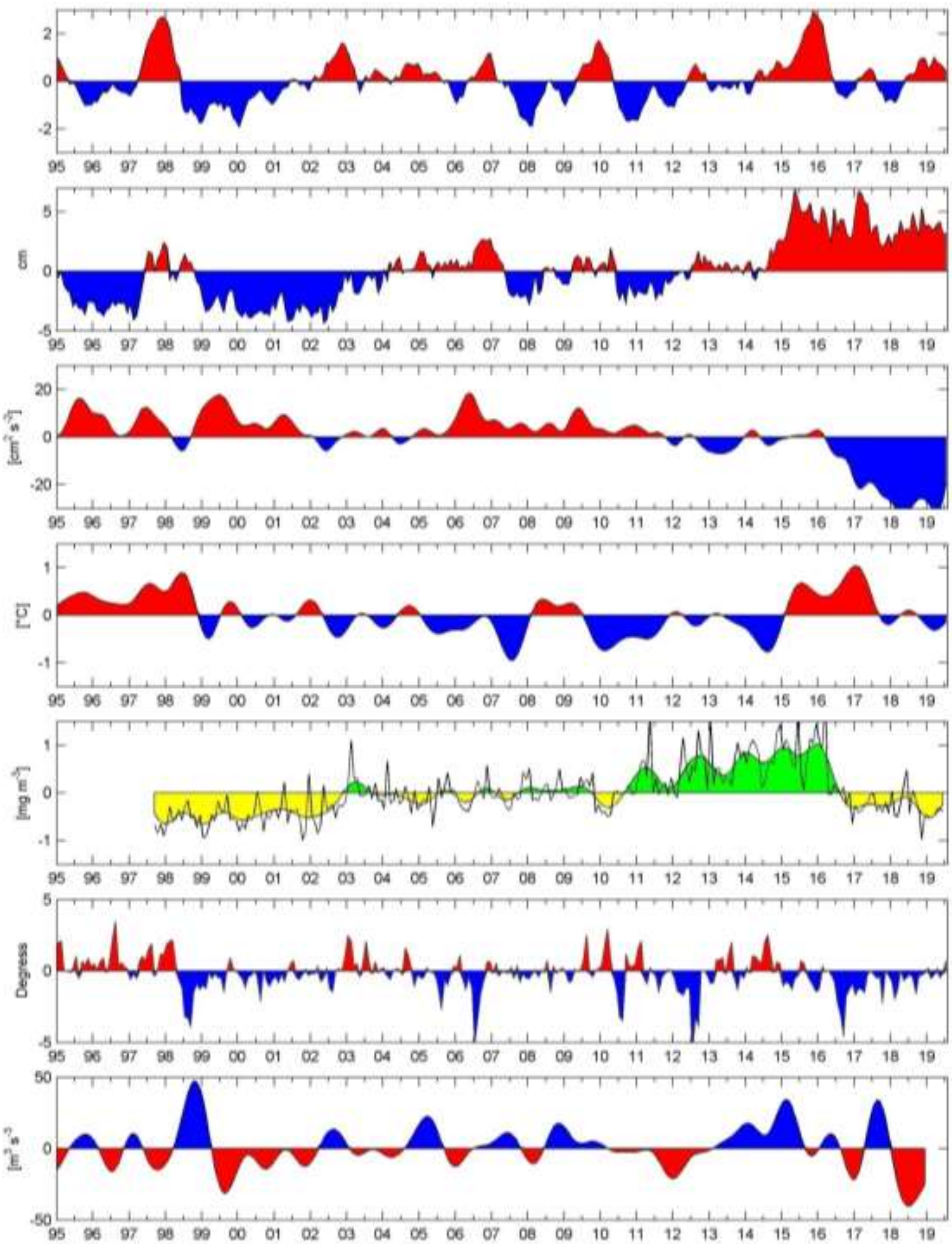

Figure 5. Time-series of environmental indexes in the area delimited by 34º - 42ºS and from the line coast to 80ºW: a) 3-4 ENSO index, b) sea level anomaly, (m) c) Eddy kinetic energy anomaly (cm^2 s^{-2}), d) sea surface temperature anomaly (ºC), e) surface chlorophyll anomaly (mg m-3), f) latitudinal anomaly of 16ºC isotherm at 80ºW (latitudinal degrees), and e) anomaly of wind induced turbulence (m^3 s^{-3}).

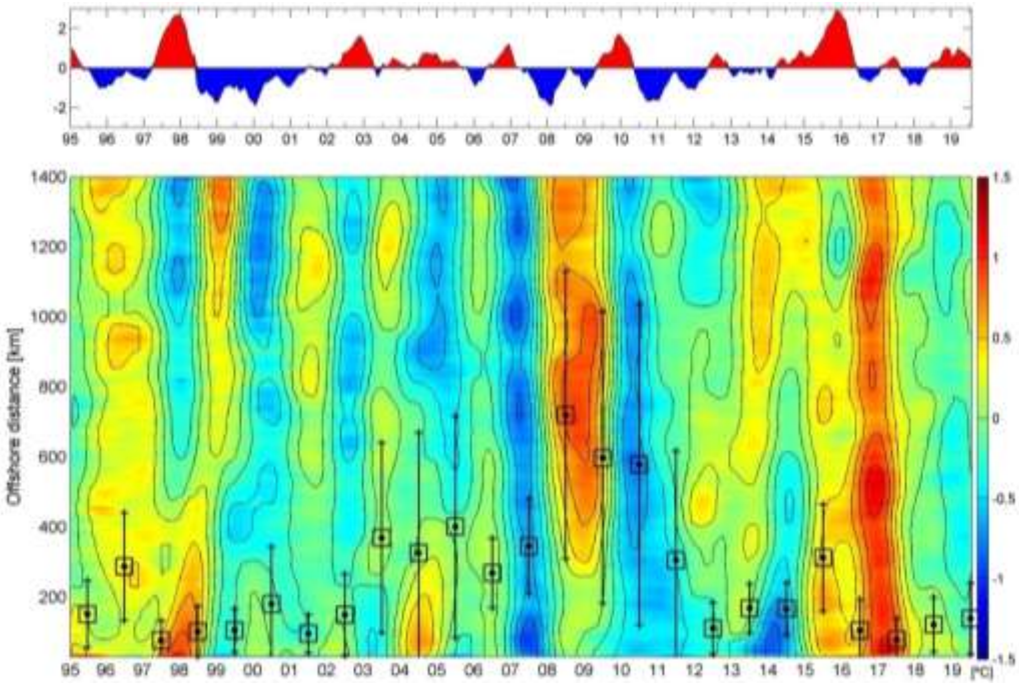

Figure 6. Space-time Hovmöller diagram of sea surface temperature anomalies (ºC) in the Chilean jack mackerel (CHJM) habitat off central-southern Chile, considering the 38ºS band. Boxes represent the CHJM mass centers for 1995-2019. Timeseries of 3-4 ENSO index variability is also included.

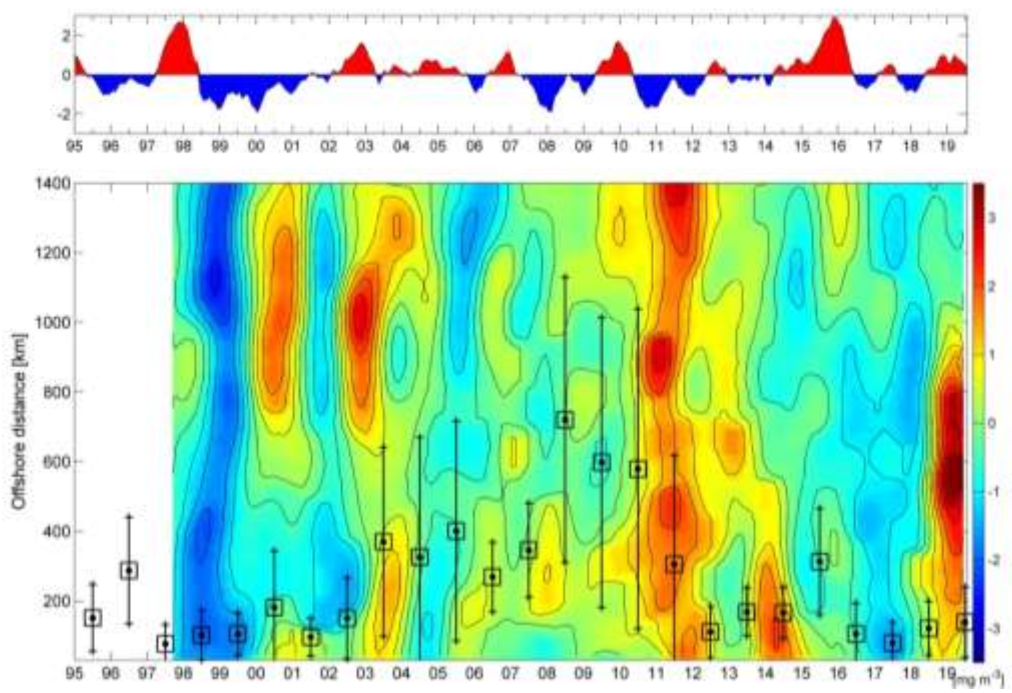

Figure 7. Space-time Hovmöller diagram of sea surface chlorophyll concentration (mg m^{-3}) in the Chilean jack mackerel (CHJM) habitat off central-southern Chile, considering the 38ºS band. Boxes represent the CHJM mass centers for 1995-2019. Timeseries of 3-4 ENSO index variability is also included.

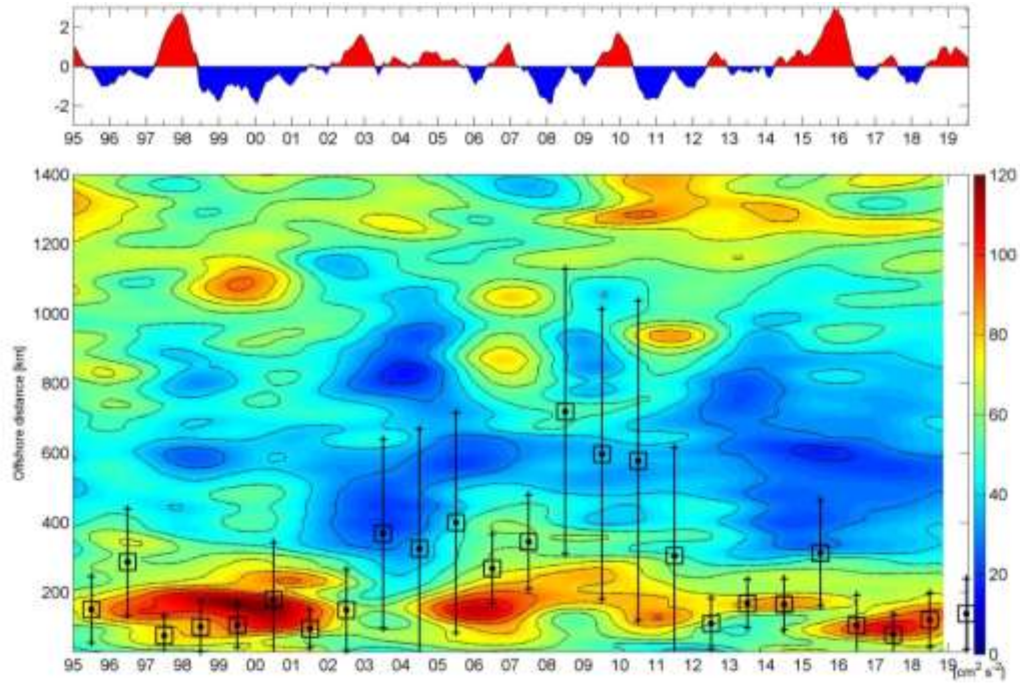

Figure 7. Space-time Hovmöller diagram of eddy kinetic energy (cm^2 s^{-2}) in the Chilean jack mackerel (CHJM) habitat off central-southern Chile, considering the 38ºS band. Boxes represent the CHJM mass centers for 1995-2019. Timeseries of 3-4 ENSO index variability is also included.