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Behaviour and size distribution of anchoveta (*Engraulis ringens*) under El Niño 2023 in the Northern Humboldt Current System

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Summary: Oceanographic conditions in the Northern Humboldt Current System (NHCS) in 2023 were warm due to the presence of El Niño 2023-2024. The Instituto del Mar del Perú (IMARPE) carried out five marine scientific activities applying hydroacoustic techniques to observe the impact on fishery resources, with the support of fishing industry vessels. This article presents the impact produced on the distributional behaviour and size structure of the anchoveta, as well as the oceanographic conditions of temperature, salinity, and oxygen. The results showed that anchoveta inertia was clearly elongated, showing a very coastal spatial distribution reaching up to 66 nm throughout 2023. At the vertical level, it reached up to 190.41 m depth due to the deepening of the oxygen minimum zone and the approach to the coast of the warm water masses. Despite these conditions, the anchoveta maintained its usual characteristics of positive spatial autocorrelation due to the continuity along the coast, structured by the high concentration hotspots and variable in time due to the characteristics of the NHCS. The anchoveta lengths were consistent in all marine research activities, the growth observed in the summer survey being mirrored in the spring survey, but their body growth was slowed.

Keywords: El Niño event; displacement; distribution; concentration; oceanographic condition; size structure.

Comportamiento y distribución de tallas de la anchoveta (*Engraulis ringens*) durante El Niño 2023 en el sistema de la corriente de Humboldt del Norte

Resumen: Las condiciones oceanográficas en el norte del Sistema de la corriente de Humboldt (NSCH) en el 2023 fueron cálidas, debido a la presencia de El Niño 2023-2024. El Instituto del Mar del Perú (IMARPE) realizó cinco actividades científicas marinas aplicando la hidroacústica para observar el impacto sobre los recursos pesqueros, con el apoyo de embarcaciones de la industria pesquera. Este artículo presenta el impacto generado el comportamiento distribucional y la estructura de tallas de la anchoveta; así como, las condiciones oceanográficas de temperatura, salinidad y oxígeno. Los resultados mostraron que la inercia de la anchoveta fue netamente alargada mostrando una distribución espacial muy costera en todo el 2023, alcanzando hasta las 66 mn. A nivel vertical, alcanzó hasta los 190.41 m de profundidad debido a la profundización de la Zona Mínima de Oxígeno (ZMO) y al acercamiento hacia la costa de las masas de aguas cálidas. A pesar de estas condiciones la anchoveta mantuvo sus características habituales de autocorrelación espacial positiva debido a la continuidad a lo largo de la costa, estructurada por los núcleos de alta concentración y variable en el tiempo por las características propias de la NSCH. Las tallas de la anchoveta fueron coherentes en todas las actividades de investigación marina, lo observado en el muestreo de verano reflejó un crecimiento reflejado en el crucero de primavera; sin embargo, su crecimiento corporal fue más lento.

Palabras clave: evento El Niño; desplazamiento; distribución y concentración; condición oceanográfica; estructura de tallas.

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INTRODUCTION

As a result of climate change, warming events in the oceans are more frequent around the world, impacting the dynamics of marine species (Santana-Falcón and Séférian 2022). These temperature increases in the oceans generate a fish size reduction related to the decrease in oxygen solubility, which is needed for body tissue production (Avaria-Llautureo et al. 2021). Fish search for areas with optimal conditions to survive when their original environment changes, and the size of the fishes is associated with their dispersion ability; the biggest ones travel great geographic distances thanks to greater speed, and the smallest ones are the most vulnerable (Avaria-Llautureo et al. 2021). The increase in sea temperature directly affects the physiology of fish (Dahms and Killen 2023). The changes in their metabolism brought about by changes in the level of oxygen in the water and the salinity reach lethal limits (Smyth and Mike 2016) and also lead to changes in their distribution (Feoma-2G 2023).

Increases in temperature constitute a physiological load that can alter the capacity of fish and may be relevant in particular situations (Sebastián and Bastien 2020). Warming increases fish growth rates, but the size structure of the population shifts towards smaller individuals, leading to lower fishery yields (Lindmark et al. 2022).

In the Northern Humboldt Current System (NHCS), diverse dynamic oceanographic processes constantly occur in the water column, generating a high climate variability at different scales: seasonal (summer-winter), interannual (El Niño-La Niña), decadal (warm and cold periods) and secular (high and low variability), generating horizontal and/or vertical displacements of fish species (Espino 2014), whose movements vary according to the intensities of these scales. Among the most abundant species is the anchoveta (*Engraulis ringens*) because of its high productivity and high environmental variability (Chávez et al. 2008, Bouchón 2018). However, throughout 2023, El Niño interannual variability occurred, characterized by the presence of warm waters on the Peruvian coast that flow from north to south (Panama current) with a strengthening of the Central American trade winds and a weakening of the southern trade winds and the Peruvian or Humboldt current. However, there are also two variants of the El Niño event: i) El Niño (global ENF), the best known with worldwide consequences, is a strong event with a temperature increase of 2°C for at least three months, and ii) coastal El Niño (coastal ENF) is a local event that is more sudden and of shorter duration (Takahashi 2017). However, the coastal El Niño 2023 in the NHCS was persistent throughout most of the year and caused temporary changes in the oceanographic environment that affected the distribution and metabolic processes of anchoveta and other marine species, as has occurred in previous El Niño events (Ñiquen and Bouchón 2004).

The management of anchoveta fishing activity in Peru is based on the best scientific information available, which is provided by the Instituto del Mar del Perú (IMARPE) through its continuous national research programmes on the sea and its living resources, mainly anchoveta. Due to the high environmental variability and oceanographic dynamics of the NHCS, IMARPE carried out many ambitious strategies of observation and monitoring of the sea that are uncommon in other parts of the world. Since its creation, IMARPE has demonstrated that only by increasing the frequency of observations on the dynamics of the sea and its living resources can we have more knowledge to recommend better decisions. Historically, the more uncertainty there has been off our coasts, such as El Niño, La Niña or other events, the more IMARPE has carried out observation actions at sea and on land. Anchoveta fishery management is therefore based on observations at sea obtained from scientific surveys, exploratory fishing, fishing surveys, EUREKAS operations and others, and on land by monitoring the pelagic fishery. These actions have enriched scientific knowledge on the state of the stock and the ecosystem, supporting the sustainability of anchoveta fisheries.

The objective of this study was to determine the changes in the spatial distribution of anchoveta at horizontal and vertical levels, their size structure and the oceanographic conditions of temperature, salinity and oxygen that generated these changes.

MATERIALS AND METHODS

Study area and participating vessels

The study area of investigation was in the sea of the NHCS between Tumbes and Tacna (03°33' to 18°21'S), up to a maximum distance of 100 nm from the coast. The details for each activity (Act) were as follows (Table 1):

i) Act 1: Survey 2302-03 of Hydroacoustic Evaluation of Anchoveta and Other Pelagic Resources, carried out between 22 February and 24 March in the north-central zone of Puerto Pizarro to Atico (03°30' to 16°03'S) with a coverage of 77340 nm^2. The following fishing vessels (FV) of the National Fisheries Society (SNP) participated: FV *Incamar 1* and FV *Tasa 425* for acoustic and oceanographic sampling; and FV *Chira I*, FV *Juancho*, FV *Galileo* and FV *Claudia* to carry out fishing sets (biological sampling). The biological sampling vessels were replaced in Casma by the following: FV *Pisco 1*, FV *Samanco 3* and FV *Tasa 43*. FV *Incamar 1* was replaced in Callao by FV *San Fernando*. A hydroacoustic assessment survey provides information on the biomass, distribution and biological aspects of the main pelagic species, as well as an update on oceanographic conditions.

ii) Act 2: Operation Eureka LXXIV carried out from 17 to 21 April 2023, in the Talara to Morro Sama area (04°34' to 18°21'S) with the participation of 20 vessels (16 industrial steel vessels and 4 industrial wooden vessels).
Operation Eureka is a rapid investigation that involves many vessels to determine qualitative distribution and sizes, in this case of anchoveta.

iii) Act 3: Hydroacoustic Survey and Other Coastal Resources 2304-06 carried out from 27 April to 1 June 2023 between Morro Sama and Paita (18°21' to 05°00'S), with the participation of FV *Imarpe V* and 4 FV of the SNP between Atico and Talara (16°03' to 04°34'S) and one wooden FV of the Asociación Nacional de Armadores Pesqueros Ley 26920 (ANAP) between Chimbote and Chicama (09°05' to 07°48'S).
This type of survey is similar to Act 1.

iv) Act 4: Monitoring of the Biological-Fisheries Aspects of Anchoveta 2307-08, carried out by FV *Imarpe V* and FV *Imarpe IV* in three replicates between 14 July and 19 August 2023 in selected areas. The first replica (Act 4: Replica 1) was between Mórrope and Chimbote (06°30' to 09°05'S) and Huacho and Pisco (11°16' to 13°42'S); the second replica (Act 4: Replica 2) between Talara and Pimentel (04°34' to 06°47'S) and Chimbote and Callao (09°05' to 12°03'S); and the third replica (Act 4: Replica 3) between Paita and Chimbote (05°00' to 09°05'S) and Casma and Pisco (09°31´-13°42´S).The purpose of monitoring is to determine the distribution and biological aspects of a species, in this case anchoveta.

v) Act 5: Survey 2309-11 of Hydroacoustic Evaluation of Anchoveta and Other Pelagic Resources carried out between 20 September and 4 November 2023. The survey was carried out between Puerto Pizarro and Sama (03°30' to 18°21'S) with the participation of FV *Incamar 2* and FV *Tasa 425* for acoustic and oceanographic sampling, and FV *San Antonio* and FV *Don Luis* for biological sampling, (between Puerto Pizarro and Casma); FV *Dorado* and FV *San Judas II* (between Casma and Cerro Azul); and FV *Costa Brava* and FV *Tasa 417* (between Cerro Azul and Chala). FV *Imarpe V* worked between Lobos de Tierra and Pisco (06°25' to 13°42´S) and FV *Imarpe IV* between Atico and Morro Sama (16°03' to 18°21'S). Two ANAP wooden vessels from Law 26920 also participated in the area between Paita and Chimbote (05°00' to 09°05'S) (FV *María Mercedes II* and FV *Milagrosa Concepción II*).
This type of survey is similar to Act 1.

Table 1. – Study area of vessels participating in each scientific activity.

Nro	Vessels	Length (m)	Distance (nm)	Study area
Act 1:	Acoustic and oceanographic sampling:			
	FV Incamar 1	77.00	0-100	Pto.Pizarro-Callao
	FV San Fernando	41.55		Callao-Atico
	FV Tasa 425	43.92	0-100	Pto. Pizarro-Atico
	Biological sampling:			
	FV Chira I	32.80	0-100	Pto. Pizarro-Casma
	FV Juancho	39.77		
	FV Galileo	34.60		
	FV Claudia	37.83		
	FV Pisco 1	42.60	0-72	Casma-Atico
	FV Samanco 3	37.46		
	FV Tasa 43	44.52		

Act 2:	20 FV of the SNP:			
	FVs: Tasa 425, Ligrun, Malena, Ribar IX, Andes 53, Tasa 417, San Antonio 3, Tasa 41, Polar IV, Patricia, Polar VII, Dorado, Ribar XVI, Marina, Rodas, Maru and Tasa 44.		0-50	Talara-Sama
	4 FVs of ANAP:			
	**FVs: Jagui, Milagros de Chalpon I, Pontevedra and María Mercedes		0-10	Talara-Callao
Act 3:	FV Imarpe V	16.50	0-10	Morro Sama-Paita
	FV Andes 53	63.05	10-40	Atico-Pta. La Negra
	FV Tasa 44	44.70	10-40	San Juan-Talara
	FV Ribar IX	58.19	10-40	Atico-Talara
	FV Tasa 43	44.52	10-40	Atico-Talara
	FV Pontevedra	20.30	0-15	Chimbote-Chicama
Act 4:	*Replica 1:*			
	*FV Imarpe V	16.5	0-40	Mórrope-Chimbote
	*FV Imarpe IV	16.5	0-40	Huacho-Pisco
	Replica 2:			
	*FV Imarpe V	16.5	0-40	Talara-Pimentel
	*FV Imarpe IV	16.5	0-40	Chimbote-Callao
	Replica 3:			
	*FV Imarpe V	16.5	0-40	Paita-Chimbote
	*FV Imarpe IV	16.5	0-40	Casma-Pisco
Act 5:	Acoustic and oceanographic sampling:			
	FV Incamar 2	77.00	0-100	Talara-Chala
	FV Tasa 425	43.92	0-90	Pto. Pizarro-Chala
	*FV Imarpe V	16.50	0-10	I. Lobos de Tierra-Pisco
	*FV Imarpe IV	16.50	0-50	Atico-Morro Sama
	Biological sampling:			
	FV San Antonio III	39.40	0-80	Pto. Pizarro-Casma
	FV Don Luis	40.00		
	FV Dorado	37.57	0-80	Casma-Cerro Azul
	FV San Judas II	48.10		
	FV Costa Brava	37.46	0-80	Cerro Azul-Chala
	FV Tasa 417	38.75		
	**FV Milagrosa Concepción II	15.85	0-40	Paita-Chimbote
	**FV María Mercedes	22.58		Chimbote-Callao

The FVs belong to the SNP, the *FVs belong to IMARPE and the **FVs belong to ANAP Law 26920.
**FVs IMARPE conducted acoustic, oceanographic and biological sampling.

Acoustic equipment

The acoustic sampling vessels were each equipped with a SIMRAD EK 80 multi-frequency scientific echosounder (frequencies: 38 and 120 kHz). This equipment was installed on the port side of the vessels. In the case of the FV *Imarpe IV*, a SIMRAD model EY 60 scientific echosounder (120 kHz frequency) was installed. These echosounders were calibrated prior to each activity. In Act 2 (Operation Eureka) it was not necessary to calibrate because different echo sounder models were used.

Sampling design

The sampling design for the scientific activities was mainly systematic, consisting of transects perpendicular to the coastline and parallel to each other (Simmonds and MacLennan 2005), with a separation of 10 nm in survey 2302-03 and 15 nm in survey 2309-11. The distance of the transects was determined according to the planning of each activity, but it was taken into consideration that this distance could vary according to the presence or absence of pelagic resources (mainly anchoveta), adverse conditions arising from bad weather or breakdowns in the vessel, as described in the acoustic protocol by Castillo et al. (2011).

The "zigzag" design was used in Act 4 Replica 3, as well as a complement in the 8 nm coastal strip of Act 2 and Act 5.

Fishing sets

The fishing gear used by the IMARPE vessels were Granton-type pelagic trawls with a vertical opening of 6 m for FV *Imarpe IV* and FV *Imarpe V*, with an effective trawling time between 8 and 25 min. The FVs that participated mainly for biological sampling used 13 mm mesh size anchovetera purse seines. The total number of fishing hauls made in the five activities were 240, 93, 211, 250 and 182, respectively.

Data processing

Acoustic data

The acoustic data post-processing is described in the "Protocol for action in the collection of data during a pelagic hydroacoustic survey" (Castilllo et al. 2011). Echo-trace identification was carried out using the EchoView software (Myriax software Pty Ltd), with which the detected species were identified according to catch composition of the fishing set, type of echo-trace and multi-frequency analysis (i.e. acoustic frequency response graphs of schools) (La Cruz et al. 2017, Castilllo et al. 2011, Simmonds and MacLennan 2005).

In the horizontal distribution plots, inertia was added, which is a measure of the dispersion of the population around its centre of gravity, that is, the root means square distance between the individual fish and the centre of gravity of the distribution (Bez and Rivoirard 2001, Woillez et al. 2007). The data from the Nautical Area Scattering Coefficient (NASC) values of the anchoveta were used. The formulation is:

$$Inertia = \frac{\sum_{i=1}^{N} z_i \ . \ (x_i - CG)^2}{\sum_{i=1}^{N} z_i}$$

$$CG = \frac{\int x \ \mathrm{z(x)} dx}{\int z(x) \ dx}$$

where z_i is the NASC value of anchoveta, x_i is the point in space (latitude or longitude) of the sample and CG is the centre of gravity. The inertia is constituted by an ellipse with a larger diameter (latitudinal) and a smaller diameter (longitudinal).

The vertical distribution of schools was made from mean depths, obtained from region exports in the EchoView software and plotted in the R program by degree of latitude or by time of day. The vertical distribution of abundance was by S_v values. To obtain the best description of the schools in the water column (S_v), the outliers were not considered. These outliers were determined by box plot scanning and comparison of means and medians. The S_v is the strength of the acoustic backscatter volume expressed in decibels referred to 1 metre (dB re 1 m^{-1}), given by the following formula:

$$S_v = 10 \ log_{10}(s_v)$$

where s_v is the coefficient of the acoustic backscattering volume expressed in m^{-1}, given by $s_v = \sum \sigma_{bs}/V$, which is the summation of all discrete targets (or also of the acoustic backscattering cross section σ_{bs}) in the volume V (MacLennan et al. 2002).

Oceangraphic data

Oceanographic sea surface temperature (SST) data were collected from the Operational Sea Surface Temperature and Ice Analysis (OSTIA) which provides daily maps at 0.05°×0.05° (1/20°) horizontal resolution, using in situ and satellite data from infrared and microwave radiometers. SST anomalies were calculated on the basis of Pathfinder climatology at a horizontal resolution of 0.25°×0.25° (1/4°) for the period 1991-2020.

As part of the analysis procedure, a bias estimate was performed on each of the contributing satellite sensors. This is done by calculating pairings between each satellite sensor and a reference data set (currently consisting of the in situ data and a subset of the MetOp AVHRR satellite data). These differences were then fed into an optimal interpolation procedure to produce gridded polarization fields at each sensor. OSTIA uses satellite data provided by the GHRSST project along with in situ observations to determine SST. For more information, see: http://ghrsst-pp.metoffice.gov.uk/ostia-website/index.html.

For the vertical oceanographic data, the Chicama section was considered because it is the most important area for the abundance of anchoveta and the one most impacted by an El Niño event. The sections close to the dates of each scientific activity were considered. The methodologies are described in IMARPE (2023a) and IMARPE (2023b). The characteristics of the water masses in the NHCS are described in Zuta and Guillén (1970), Grados et al. (2018).

Biological data

Biological data on the size structure of anchoveta were collected from the fishing hauls conducted in each scientific activity. The size structure was weighted according to the NASC values of anchoveta (three values before and after each set with anchoveta present), described in IMARPE (2023a) and IMARPE (2023b).

RESULTS

Anchoveta spatial distribution: centre of gravity and inertia

In general, the horizontal distribution of the anchoveta was clearly coastal throughout the year, reaching its greatest longitudinal distance up to 66 nm from the coast, as recorded in Act 1 (survey 2302-03). In Act 2 it was recorded up to 50 nm offshore and in Act 3 up to 40 nm offshore. In Act 4 in replicate 1 it recorded up to 40 nm from the coast, in replicate 2 up to 28 nm from the coast and in replicate 3 up to 42 nm from the coast. Finally in Act 5 (survey 2309-11) it was recorded up to 60 nm from the coast. Another characteristic of its spatial distribution is that it is highly variable, structured and dependent in space and time: i.e. the distribution constantly varied in terms of weeks, in its distribution structure it had high concentrations that were located in different zones of its distribution, and it had continuity along the coast, that is, it had positive spatial autocorrelation in which the latitudinal probability of finding a school was high due to the characteristics of its habitat.

The centre of gravity was variable due to the displacements made by the anchoveta as a result of oceanographic conditions. The centre of gravity in the activities studied did not show trends towards the south, indicating that there was not a strong migration towards this region due to the presence of warm waters, except in Act 2, which was in front of Chancay.

Inertia was wide in Act 2 due to the larger longitudinal diameter resulting from the presence of anchoveta, which was recorded in several areas up to 50 nm offshore in the north between Pimentel and Pacasmayo and in the south between Chala and Atico. Another distribution with considerable inertia was found in Act 5, in which anchoveta was recorded up to 60 nm offshore between Salaverry and Casma, with records of high concentrations retracted to the coast, in both the north and south. The narrow ellipses with reduced longitudinal diameters indicated that the highest abundances of anchoveta had retreated towards the coast, as recorded in Act 1, Act 4 (in the three replicates) and Act 3. In the penultimate activity (Act 4), the replicates were conducted in selected areas (Fig. 1) mentioned above and all showed a distinctly shoreward distribution (ellipses with narrow longitudinal diameters).

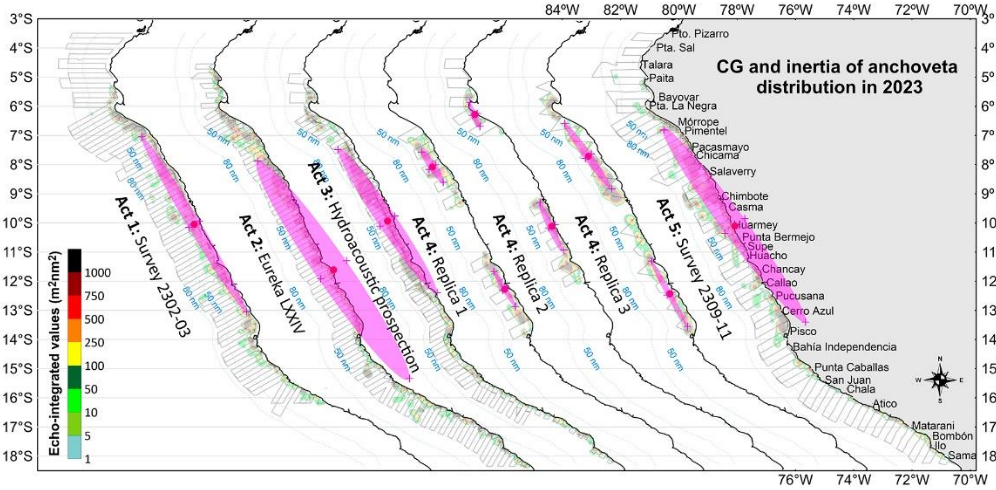

Fig. 1. – Location of the inertia (pink filled ellipse) and centre of gravity (pink dots) of the anchoveta distribution in the marine scientific activities carried out in 2023. Act 1, 22 February-24 March; Act 2, 17-21 April; Act 3, 27 April–01 June; Act 4: 14 July–19 August; and Act 5, 20 September–04 November.

Anchoveta vertical distribution

The vertical distribution of anchoveta was variable, fluctuating in the activities carried out: i) in Act 1 it was recorded up to 99.61 m, the deepest schools being between Paita and Pacasmayo. ii) in Act 2 it was found up to 115.12 m, the deepest schools being recorded on a large part of the coast located in Sechura, Callao-Punta Bermejo, Pisco and Atico-Quilca; iii) in Act 3 it was recorded up to 190.41 m, the deepest schools being detected between Paita and Pucusana; iv) in Act 4, three replicates were carried out in two selected areas, the first recording to depths of 124.50 and 139.75 m, the second to depths of 98. 54 and 119.91 m and the third to depths 127.53 and 142.24 m depth; v) in Act 5 schools of anchoveta were detected up to 127.69 m depth, with the deepest schools being recorded in two areas, the first between Chicama and Salaverry and the second between Atico and Quilca.

However, when the school regrouping was analysed by time of day, we noticed that the anchoveta in 2023 had a nictemeral behaviour; that is, during the day they were found at greater depths and at night mainly in the surface layer of 40 m. The details of this behaviour are as follows: In Act 1 there were some schools located up to 99.61 m, then in Act 2 the depth increased, reaching 190.41 m depth in Act 3 and 127.69 m in Act 5. This temporary vertical displacement behaviour (Fig. 2) was due to the oceanographic conditions present in the coastal waters, which led the anchoveta to ascend to the surface layer to feed at night.

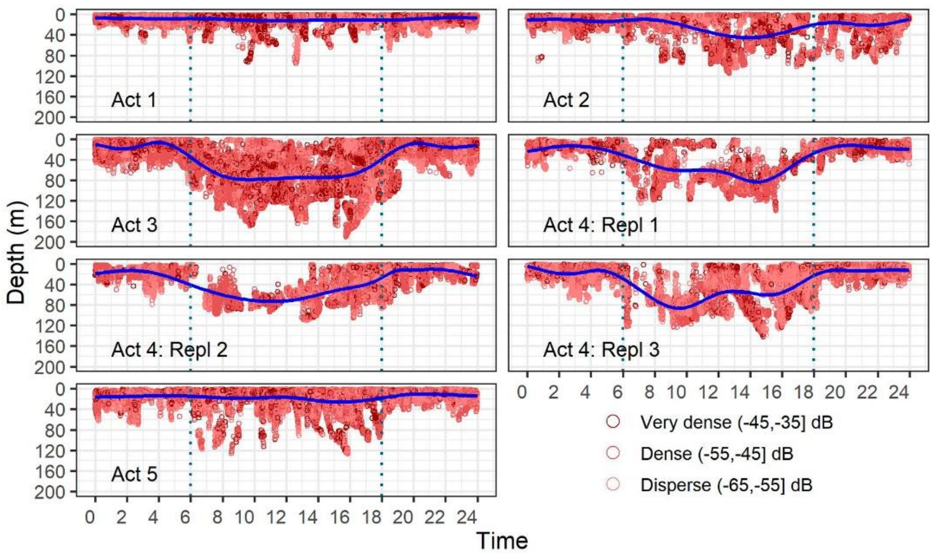

Fig. 2. – Trend of the vertical distribution of anchoveta schools in categories of abundance by time of day (blue lines) in the marine activities carried out in 2023. Dash lines between 6 a.m. and 6 p.m. correspond to the day hours.

Oceanographic conditions in the activities carried out

At surface level

In January, there were negative anomalies, mainly south of Paita, corresponding to cold environments. In February, warm conditions were recorded in the northern zone (the Niño 1+2 region), which expanded in front of Peru, associated with the projection of temperatures higher than 22°C towards the south, and this warming intensified, reaching anomalies of up to +4°C between Paita and San Juan de Marcona after a fortnight in March, when Act 1 was ending in the south.

In the first weeks of April, the maximum warming was recorded, with anomalies of +7°C in Paita. In the last week of April, Act. 2 was started. Starting in May, the positive anomalies gradually declined associated with the northward and westward retreat of waters above 25°C towards the coast, but high temperatures were maintained, with anomalies of up to +4°C until September in the area between Tumbes and San Juan de Marcona. Under these conditions, Act 3 and Act 4 were carried out, and the anchoveta was found to have retreated towards the coast.

Starting in the second half of September, the SST in the coastal marine area began to decrease and showed a wide distribution of temperatures between 18° and 20°C, indicating a significant decrease in warming with a predominance of +1°C anomalies recorded until December 2023, thus indicating the transition of El Niño from strong to moderate category according to reports of the Coastal El Niño Index (ICEN). Under these conditions Act 5 was performed.

It should also be noted that between May and December 2023 (Fig. 3) there was a greater number of arrivals of warm Kelvin waves off South America that were associated with the occurrence of the El Niño episode in the Ecuadorian Pacific, which allowed positive SST anomalies to be maintained on the Peruvian coast.

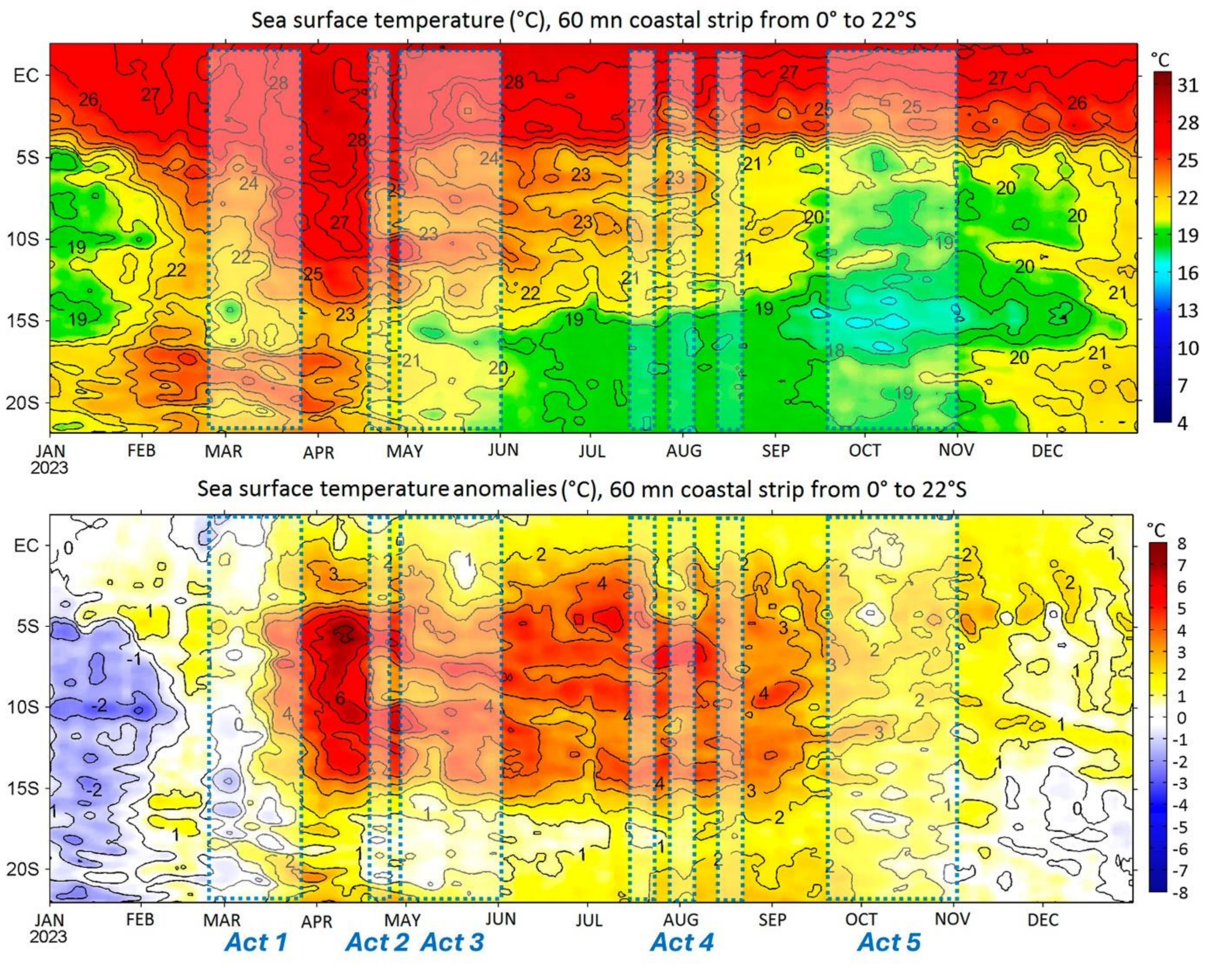

Fig. 3. – Daily average SST variation and thermal anomalies (°C) for the 60 nm coastal strip and marine activities conducted in 2023. Data: OSTIA-UKMO-L4-GLOB-2.0.

At subsurface level

The structure of the water column off Chicama changed over time according to the evolution of El Niño 2023. In March, a well stratified thermocline was observed above 50 m depth, associated with positive thermal anomalies of up to +3°C; however, in the 50 to 100 m thermocline, slight negative anomalies were maintained, and the warming process increased, showing warm conditions throughout the water column in April. In May, the thermal increase continued, reaching anomalies of more than +6°C, although below 100 m the thermal conditions normalized. In July, the warm conditions again expanded throughout the column, but with lower temperatures and anomalies (+4°C) due to the decline of the warm event. In October, temperatures decreased, but the warm condition was maintained in the water column, with anomalies greater than +1°C above 120 m and between +05°C and 1°C between 120 and 250 m depth.

The haline structure also showed major changes due to the unusual presence of the equatorial surface waters (ESW) in this area, with mixing processes observed in March between this water mass and the sea surface water (SSW) and coastal cold water (CCW).

In April the presence of these water mixing processes was evident above 50 m throughout the section, but in May they retreated to the west, remaining outside 25 nm and above 60 m, On the other hand, in July the SSW prevailed above 180 m depth. Subsequently, in October the mixing processes (SSW and CCW) dominated over 100 m, with an SSW cell over 15 m outside the 30 nm and a greater influence of the CCW in the coastal zone.

In March, anchoveta were found in oxygenated waters located close to the coast up to 18 nm, reaching a depth of 60 m. In April, they maintained its vertical distribution up to 82 m depth and up to 27 nm of the coast, in oxygenated waters. The oxygen minimum zone (OMZ at 0.5 mL L^{-1}) was found to be located between 120 m (at 100 nm) and 220 m (platform). In May, the water column above 120 m continued to be oxygenated, with anchoveta recorded up to 120 m within 26 nm offshore. However, within 60 nm below 120 m, oxygen levels decreased, making the OMZ 20 to 40 m shallower than in April. In July, the oxygenated layer expanded, showing concentrations of 2 mL L^{-1} up to 180 m, and anchoveta were recorded up to 108 m depth between 5 and 38 nm from the coast. In October this layer decreased, so the OMZ was located around 130 m and anchoveta were recorded up to 128 m depth in the coastal strip of 50 nm, as shown in Figure 4.

The behaviour of the isotherms in the coastal zone and that of the iso-oxygen isotherms suggest that upwelling processes were active in all the periods analysed. However, the upwelling water corresponded to mixing waters (ESW, ASW and CCW) until before May, then it corresponded to SSW in July and mixing (SSW and CCW) in October.

In a Hovmöller diagram in the Chicama area in 2023 (Fig. 5), it was observed that the OMZ value deepened in mid-March, reaching 230 m depth by the end of May, and then rose to 120 m in the first days of August. The OMZ value deepened again to 180 m depth by the end of September, ascended again by the end of October, and then declined by the end of December 2023. This vertical behaviour of oxygen was observed in a large part of the Peruvian coast, and the vertical distribution of the total schools of each activity showed that this deepening of the anchoveta was located in oxygenated waters. In Act 3 and Act 4 the highest abundances were recorded between 75 and 120 m depth, while in Act 1, Act 2 and Act 5 they were recorded in shallower area.

Anchoveta size structure

The anchoveta sizes observed during 2023 fluctuated between 3.0 and 15.5 cm total length (TL). In Act 1 the individuals were between 3.5 to 15.5 cm TL with a main mode at 6.5 cm and a secondary one at 8.0 and 11.5 cm TL, and 82% in number were smaller than the minimum size. These individuals were growing, as observed through the activities at sea carried out from summer (Act 1) to spring (Act 5) at the end of the austral year. In Act 2, the changes observed in Act 1 were confirmed by the decrease in the availability of adults and the increase in juveniles (85%). Subsequently, in Act 3 and Act 4 an increase in the high incidence of juveniles was observed, with more than 90% in number. Finally, in Act 5, the sizes fluctuated between 6.0 and 15.5 cm TL, with a trend at 11.5 cm TL and the number of individuals below the minimum size decreased to 67%. It should be noted that this mainly unimodal structure (mode at 11.5 cm TL) was formed by individuals of approximately 1.0 years old born in the reproductive process of winter-spring 2022. Likewise, we observed the absence of individuals with a mode at 8.0 cm TL (approximately half a year old) that must have come from the Act 1 spawning of 2023 (Fig. 6). It is likely that the spawning was impacted by the 2023 El Niño event.

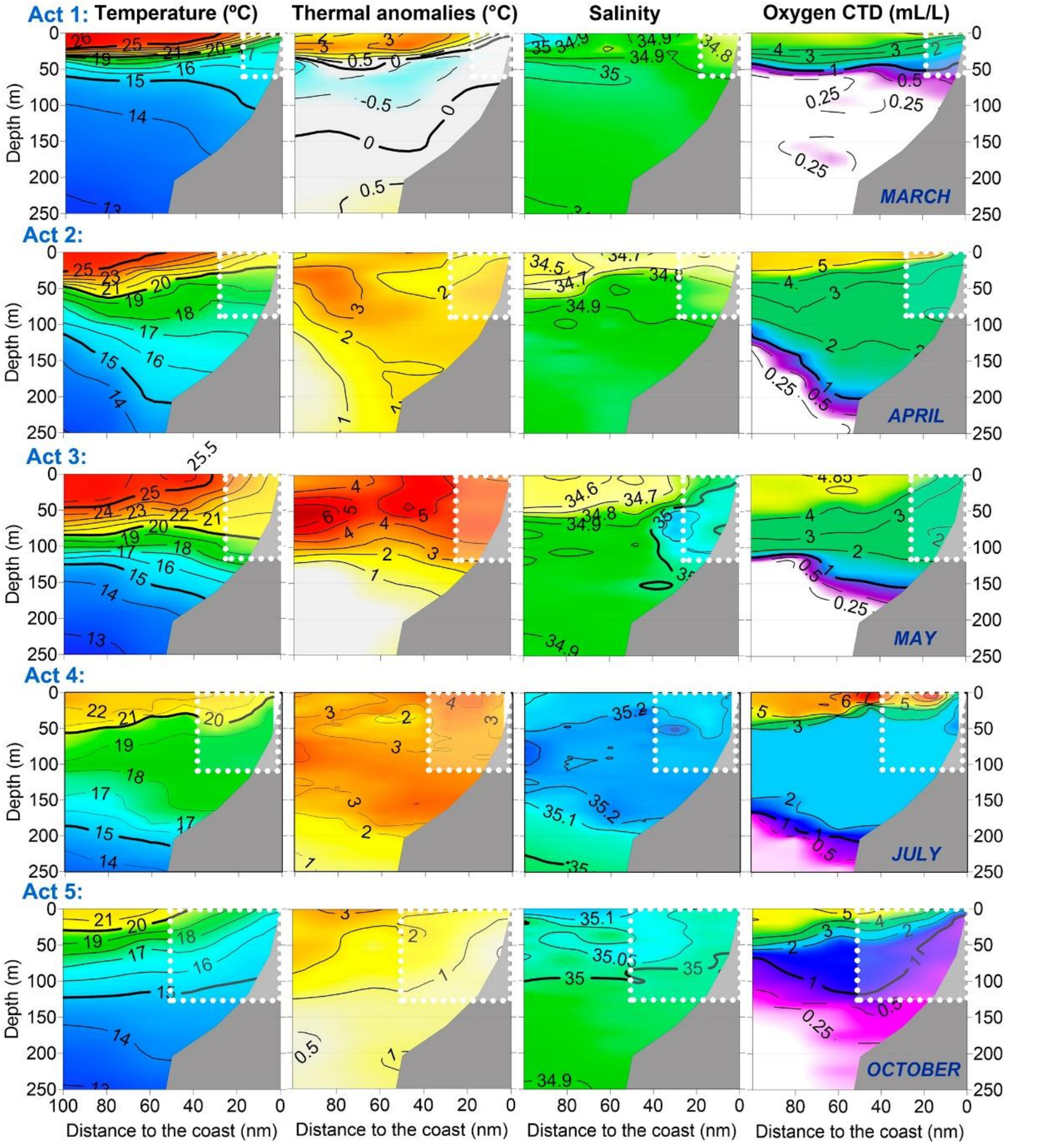

Fig. 4. – Vertical distribution of temperature (°C), thermal anomaly (°C), salinity and oxygen (mL L^{-1}) in the Chicama section for each activity. In Act 1, the hydrographic profile was performed on 6 March 2023; in Act 2 on 25-26 April; in Act 3 on 24-25 May; in Act 4 on 19 July; and in Act 5 on 21-22 October. The coastal transparent boxes correspond to the depth and distance to the coast where the schools of anchoveta were located.

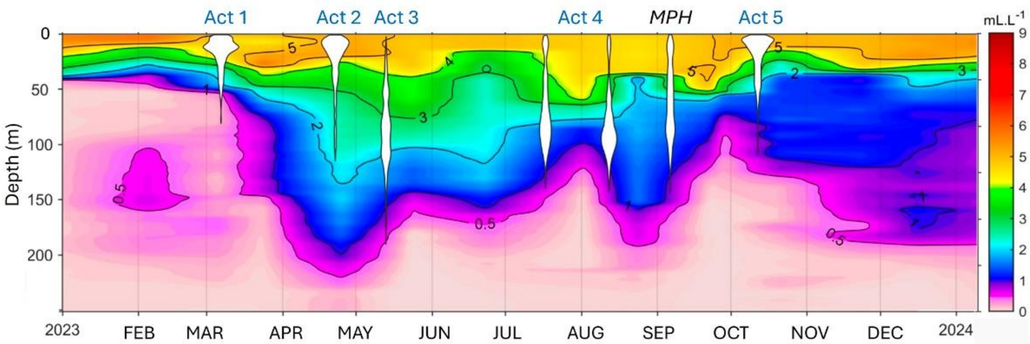

Fig. 5. – Hovmöller plot of the vertical distribution of oxygen in Chicama in 2023 with violin plots representing the depth of the total anchoveta schools in each activity. In this graph we added the anchoveta spawning biomass survey by the egg production method carried out in September 2023. This survey shows a uniform abundance of schools at the vertical level and in Act 5 the highest percentages were recorded in the surface layer of the sea.

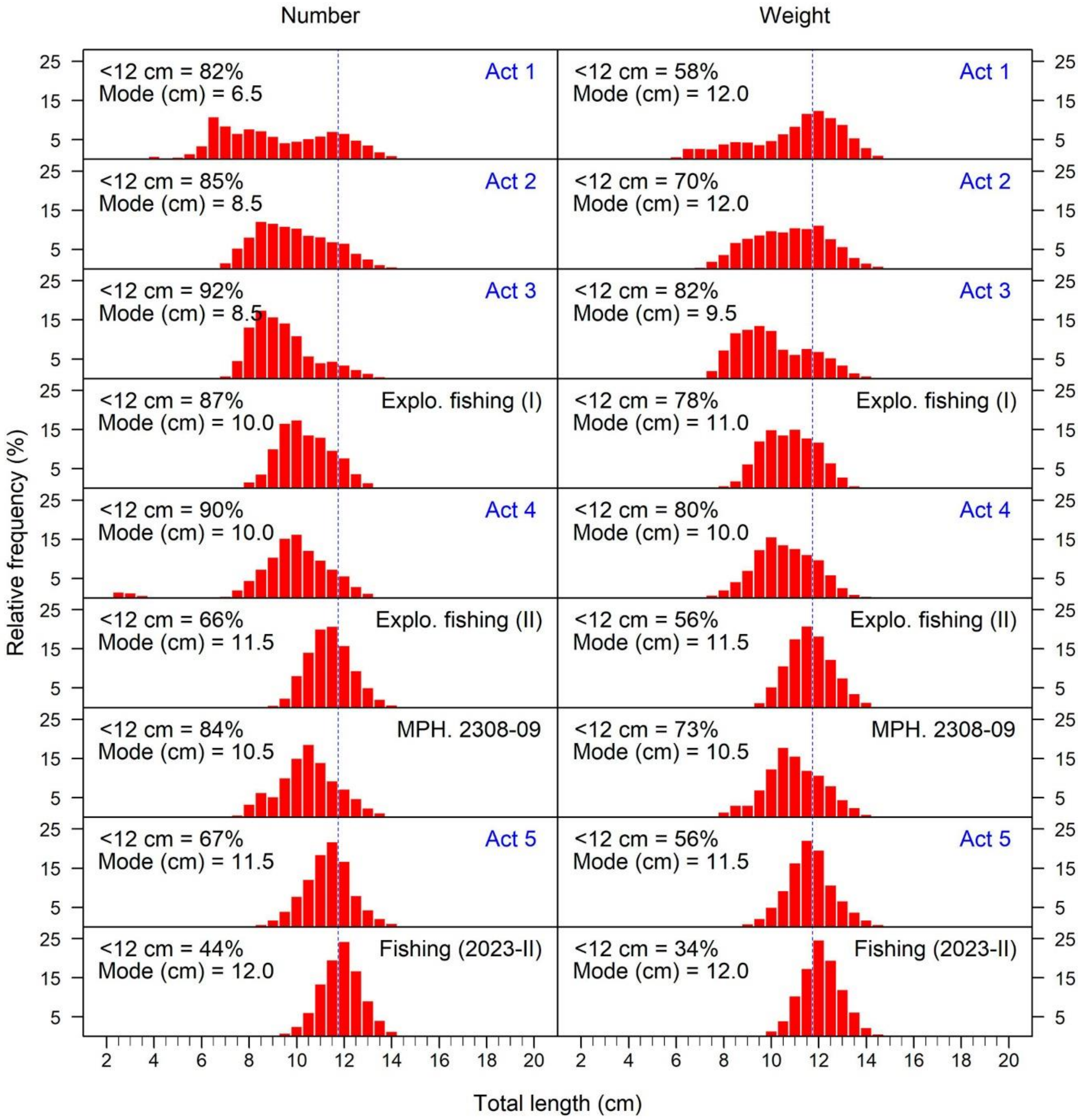

Fig. 6. – Sequence of anchoveta size structure in the activities analysed with other fishing activities and marine operations. The blue letters refer to the five hydroacoustic activities analysed.

DISCUSSION

Marine species, particularly anchoveta, have always suffered impacts from anomalous warm events in the NHCS such as those that occurred in El Niño events of strong or extraordinary intensity in 1972, 1982-83 (Espino 1999), 1997-98 (Ñiquen and Bouchón 2004) and 2015-2016. Bouchón (2018) and Peña Tercero (2019) mentioned that these events affect the physiological state and reproduction of the anchoveta due to increased temperature, food quality and intraspecific competition for the scarce refuges available near the coast. The increase in temperature throughout the year 2023 caused i) horizontal displacements towards the coastal strip due to the approach of SSW, and ii) vertical displacements of up to 190.41 m of the schools of anchoveta, as recorded in April and May (Act 3), as a consequence of the deepening of the OMZ (Casma-Cerro Azul), which allowed this depth to be reached. Espino (1999) mentioned that in El Niño 1997-98 the anchoveta was found below 100 m depth in the months of December 1997 and January 1998, and Gutiérrez (1997) mentioned that in El Niño 1997-98 anchoveta reached mainly between 90 and 150 m depth between Callao and San Juan de Marcona at the beginning of August 1997.

The vertical distribution of the schools of anchoveta were recorded at greater depths in the El Niño 2023-2024 event than in the last El Niño events of strong or extraordinary magnitude (Fig. 7) mentioned by the ICEN with. However, the anchoveta did not always remain at this depth; in Figure 2 of the vertical distribution by time of day, it was observed that in the evening hours they ascended to the surface layer of approximately 40 m to feed and then went deeper during the day, an unusual nictemeral behaviour for the anchoveta that is similar to that of other mesopelagic species such as the *Vinciguerria* and myctophids. Castillo et al. (2022) mentioned that anchoveta schools with TL larger than 10 cm are those found in the zone of physiological stress both longitudinally (away from the coast) and vertically (near the bottom). This vertical behaviour was observed in the activities carried out in 2023, making the population inaccessible to the fishing fleet purse seine nets.

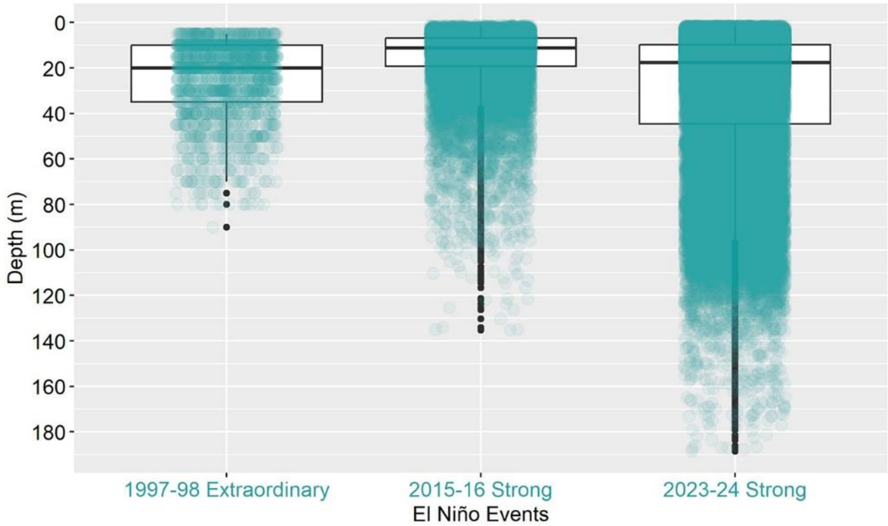

Fig. 7. – Vertical location of schools of anchoveta recorded in recent strong and extraordinary El Niño events.

Despite the impact of warm conditions on the usual behaviour of the anchoveta in 2023, it maintained its own characteristics, described in Castillo et al. (2019), such as i) continuity in its latitudinal distribution along the coast with characteristics of spatial autocorrelation, ii) structuring with hotspots or areas of high concentration in its distribution, and iii) high variability in their spatio-temporal distribution due to continuous environmental changes or the dynamics of the NHCS.

Anomalous event such as El Niño generate physiological changes in the anchoveta related to its body condition, spawning intensity, recruitment, feeding and migratory behaviour, which were studied between 1977 and 1979 during the ICANE programme, described in Dickie and Valdivia (1981), Morón and Sarmiento (2001). However, these temporary physiological changes will affect the anchoveta population depending on the magnitude and intensity of the event and the fishery regulation measures.

Regarding oceanographic conditions in the NHCS, the Technical Report of the National Study of the El Niño Phenomenon (ENFEN) reported an ICEN of –0.29 in January 2023, considering a neutral condition (Enfen 01, 2023), according to the rates of Takahashi et al. (2014) and Takahashi and Reupo (2015). Also, in February 2023, the LABCOS indexes mentioned by Quispe and Vásquez (2015) indicated a shift from a neutral to a warm condition, and then in May the maximum ICEN value of +3.54 was considered a *strong* magnitude El Niño event. In general, El Niño reached a *strong* category in the May-July quarter (ICEN+2.94), *very strong* (LABCOS +3.46) with a maximum expression in July, and a decline until November. The technical reports and communiqués from the continuous monitoring of El Niño in 2023 allowed marine activities not foreseen for this year to be carried out and allowed fishery management decisions to be recommended.

The results obtained in the biometric sampling of the size structure (Fig. 6) observed in Act 1 showed a growth coherence with the size structure observed in Act 5 if we add to these activities the fishing operations and data from the survey of Spawning Biomass Assessment of Anchoveta (survey 2308-09) by the egg production method also show coherence with the sizes. In all activities, no groups of specimens larger than 14-15 cm were observed. In the fishing operations carried out by the industrial and artisanal fleets, the structure was generally larger than in the research activities due to the selectivity of the school catches, generally those of higher reflectivity, which generate adult specimens and are made up of dense echotraces (IMARPE 2022). Goicochea and Arrieta (2008), mentioned that during an El Niño event the TL is less than it is in a normal year. Some researchers such as Atkinson (1994) and Ohlberger (2013) mention that individuals of fish farmed in warmer temperatures develop faster and mature earlier but reach smaller adult body sizes. Also, Avaria-Llautureo et al. (2021) mention that fish are adapting to the increase in sea temperature at an average rate of 0.8°C per million years, that this puts them at double risk due to climate change and overfishing, which are causing a reduction in the body size of fish, and that in the long term their biomass is decreasing. They mention that every time fishes experience high temperature they decrease in size as an adaptation and survival mechanism in response to the increase in high temperatures. Brett and Groves (1979) also mention that with an increase in sea temperature, fish prioritize their energy (fat reserves) in the following order: survival (basal maintenance), locomotion (movement), reproduction (spawning) and growth (body size). In these situations, it is likely that an increase in temperature can influence the size of the anchoveta in the NHCS, and more studies would have to be carried out to confirm the findings of these authors.

We believe that, in the activities carried out in 2023, a fraction of the adult anchoveta population found near the bottom were not caught due to the inaccessibility of the fishing nets and that they were not sampled to obtain their biometric measurements.

Bouchón (2018) and Peña Tercero (2019) also mention that after the warm events that occurred in the NSCH, the recovery of the anchoveta population was fast, due to its response to the normalization of environmental conditions that decreased its mortality. We believe that the adaptability of the anchoveta to the dynamic environmental conditions of the NHCS and its conservation strategy in the face of warm events of intensity and magnitude lower than “extraordinary” determines its resilience and continuity in the ecosystem, as partly mentioned by Castillo et al. (2019), and that the measures adopted for its fishing extraction will determine its sustainability.

CONCLUSIONS

During the 2023 El Niño event, the horizontal distribution of the anchoveta was mainly coastal due to the advance of warm waters towards the west and north coast, with greater intensity or retreat between the months of April and August, which were also observed in the inertia of the distribution in the various activities. Due to the advance of the warm water masses and the deepening of the OMZ, the anchoveta made vertical displacements, reaching up to 190.41 m depth between April and May.

In 2023 the anchoveta maintained its usual characteristics of positive spatial autocorrelation due to the continuity along the coast, structured by the high concentration cores and variable in time because of the characteristics of the NHCS. The size structure of anchoveta was consistent throughout the year. Observations in the summer survey reflected higher growth in the spring survey, but body growth was slowed.

The anchoveta adapts to the dynamic oceanographic conditions of the NHCS and its conservation strategy through horizontal and vertical movements, determining its continuity and resilience in the ecosystem.

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AUTHORS’ CONTRIBUTION STATEMENT

Pedro Ramiro Castillo: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Supervision, Writing – review and editing. **Marilú Bouchón:** Writing – review and editing. **Luis Vásquez:** Writing – review and editing. **Gustavo Cuadros:** Software, Graphics. **Daniel Grados:**

Supervision, Methodology, Software, Review. **Carlos Valdez:** Software, Graphics. **Marissela Pozada-Herrera:** Software, Graphics.

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