

12th MEETING OF THE SCIENTIFIC COMMITTEE

30 September to 05 October 2024, Lima, Peru

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***Dosidicus gigas* early life stages drift model off Peru:
Identifying potential spawning areas**

Peru



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DOSIDICUS GIGAS EARLY LIFE STAGES DRIFT MODEL OFF PERU: IDENTIFYING POTENTIAL SPAWNING AREAS

by

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This report contains information on the jumbo flying squid fishery in Peruvian jurisdictional waters that, we reiterate, the delegation of Peru, in use of its discretionary powers, voluntarily provides for the purpose of information and support to the scientific research work within the Scientific Committee of the SPRFMO. In doing so, while referring to Article 5 of the Convention on the Conservation and Management of High Seas Fishery Resources in the South Pacific Ocean and reiterating that Peru has not given the express consent contemplated in Article 20 (4) (a) (iii) of the Convention, Peru reaffirms that the decisions and conservation and management measures adopted by the SPRFMO Commission are not applicable within Peruvian jurisdictional waters.

2024

***Dosidicus gigas* early life stages drift model off Peru: Identifying potential spawning areas**

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1 Abstract

The spatial distribution of mature females (stages 3 and 4) of the three morphotypes (small, medium and large) was mapped for use as proxies of spawning potential. Two spawning hotspots of *Dosidicus gigas* were identified, one in the north and one in the south of Peru. The aforementioned areas were utilized as spawning zones for early life stage drift experiments over a 30-day period. It was observed that the northern area exhibited greater spatial and temporal variability (on a seasonal scale) in dispersal patterns, particularly along the longitudinal axis. The northern zone was distinguished by a higher loss of spawned individuals in surface layers (5-15 m) transported offshore even up to Galapagos Islands, while the southern zone demonstrated superior conditions for retention.

Keywords: *Dosidicus gigas*, mature females, early life stages, Ichthyop

2 Introduction

The Jumbo flying squid (*Dosidicus gigas*), an omastrephid species, is primarily associated with upwelling areas (Tafur & Rabí, 1997), characterised by their high productivity and nutrient content (Kämpf & Chapman, 2016). These conditions provide an abundant food source, enabling to sustain its high metabolic rates and rapid growth, which results in a short life span for the species (Argüelles *et al.*, 2001), in addition to its semelparous condition, which is characterised by a single reproductive pulse at the end of its life cycle (Markaida *et al.*, 2004).

D. gigas is distributed throughout the Pacific Ocean, with high concentrations in the Humboldt and California ecosystems. In these regions, *D. gigas* has exhibited a high degree of variability in its population structure, with the presence of up to three distinct morphotypes characterised by differences in the mantle length in mature individuals, including both females and males (Markaida *et al.*, 2004; Nigmatullin *et al.*, 2001).

Although the substantial abundance of biological studies on juveniles and adults of *D. gigas*, a gap remains in the study of its Early Life Stages (ELS), despite the fact that it is well known that these stages are crucial periods for the survival of individuals and subsequent impact on adult populations in most marine species (Stige *et al.*, 2019). One of the first attempts to explore the dynamics of ELS was described in the California ecosystem by Ramos *et al.* (2017) with the aim of characterising the spawning habitat of this species. Then, we propose a spatial analysis to identify potential spawning areas by morphotype and to explore how these will influence (through ocean currents) the trajectories and distribution of *D. gigas* ELS off the Peruvian coast using a Lagrangian modelling tool called Ichthyop.

3 Methods

3.1 Spatial identification of spawning areas by morphotype

The insufficient sampling of ELS (paralarvae) of *D. gigas* precludes the observation of a general pattern of spawning areas. Furthermore, the paralarvae can be confused with those of other similar species. Then, the mapping and identification of spawning areas was conducted using only mature female individuals. The degree of sexual maturity of females is determined by a macroscopic observational method, with values ranging from 1 to 4. This method was compared with maturity indices described by [Markaida & Sosa-Nishizaki \(2001\)](#), indicating that it is capable of correctly discriminating mature individuals (grade 3 and 4) from immature ones (grade 1 and 2). Subsequently, the mature females were classified into three categories (size groups) based on mantle length (*mm*, Fig. 1), as described by [Nigmatullin et al. \(2001\)](#): *small*, *medium*, and *large*.

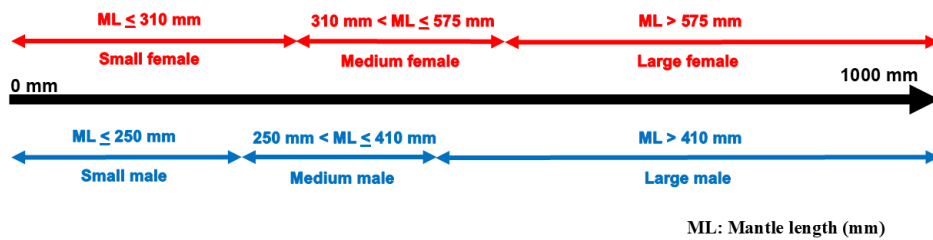


Fig. 1: Proposed size range limits (for females and males) to discriminate length groups based on the size ranges proposed by [Nigmatullin et al. \(2001\)](#). ML = mantle length (mm)

The data used to map potential spawning areas were collected by [Instituto del Mar del Perú \(IMARPE\)](#) through survey cruises and fisheries monitoring between 1989 and 2023. A general distribution map of mature individuals was generated, as well as a distribution map of mature individuals by size group, using the longitude and latitude of individuals sampled in the fishing area. The latitudinal range of the mapping was 3°-20°south. It should be noted that between 1991 and 2011, [IMARPE](#) on-board observers collected fishery biological information in the foreign flag fleet (Japan, Korea, and China) in accordance with international agreements and concessions.

3.2 3D Lagrangian model

An **individual-based model (IBM)** simulates populations and communities by following individuals and their properties (DeAngelis & Grimm, 2014). The IBM used here was the lagrangian tool **Ichthyop**, (Lett *et al.*, 2008), version 3.2.

Ichthyop is an open-source software (download from: [Github](#)). This tool allows us to study the effects of physical factors (ocean currents) on planktonic individuals dynamics by simulating the movement (in 3D) based on stored data provided by a hydrodynamic model (ROMS/CROCO, MARS, or NEMO). The stored data, which includes currents, temperature and salinity, varies in time and space and are imposed on the individuals.

In general, a protocol designed for this type of IBM approach will be followed (Grimm *et al.*, 2006, 2010) in order to explore the dynamics of *D. gigas* ELS.

3.2.1 Purpose

To assess the effect of ocean currents on dispersal patterns of ELS of *D. gigas* in two spawning areas off Peru.

3.2.2 Entities and state variables

The model included two types of entities: the environment and the individuals (virtual particles). The environment was represented by stored hydrodynamic simulations from the **Coastal and Regional Ocean COmmunity model (CROCO, Hilt *et al.* (2020); Shchepetkin & McWilliams (2005))** providing the forcing state variables: ocean current velocities (ms^{-1}), over the Humboldt Current system. Individuals were characterized by the following state variables: age (d) and location in 3D (longitude, latitude and depth).

The hydrodynamic model configuration extends from $22^{\circ}S$ to $5^{\circ}N$ in latitude and from $96^{\circ}W$ to $70^{\circ}W$ in longitude, with a horizontal resolution of ~ 10 km and 32 vertical levels. The bathymetry comes from the STRM30 dataset (Becker *et al.*, 2009). For further information regarding the hydrodynamic configuration of the model, please refer to Flores-Valiente *et al.* (2023).

Climatological simulations were run for 10 years, the first 4 years being considered as a spin-up. In the present study, the last three years were used to force [Ichthyop](#).

3.2.3 Initialization

In each simulation, a total of 1984 individuals were released at fixed positions, as identified through the process of spawning area mapping (Section [3.1](#)) each month at days 1, 10 and 20, during the three climatological years used. Four spawning depths (*5m*, *15m*, *25m* and *35m*) were employed, based on the vertical distribution of paralarvae samples. Although deeper spawning has been documented, it was not considered in this study because the ocean is more stable at greater depths, which would not significantly impact dispersal patterns.

3.2.4 Transport model

To simulate particle transport, virtual individuals were advected using a trilinear interpolation scheme of the velocity fields derived from [CROCO](#), in time and space, and using a forward Euler numerical scheme with horizontal diffusion following [Peliz *et al.* \(2007\)](#).

3.2.5 Simulations and sensitivity analysis

After each simulation, the distance traveled by each individual (particle) was calculated and analyzed according to the month of spawning, the distance to the coast at spawning and the spawning area (*north*, 2-8 °S or *south* 14-17 °S).

4 Results

4.1 Spawning areas by morphotype

The distribution of mature females (grades 3 and 4) revealed the existence of two hotspots in the north and south zones (Fig. 2), respectively, where the presence of mature females is concentrated.

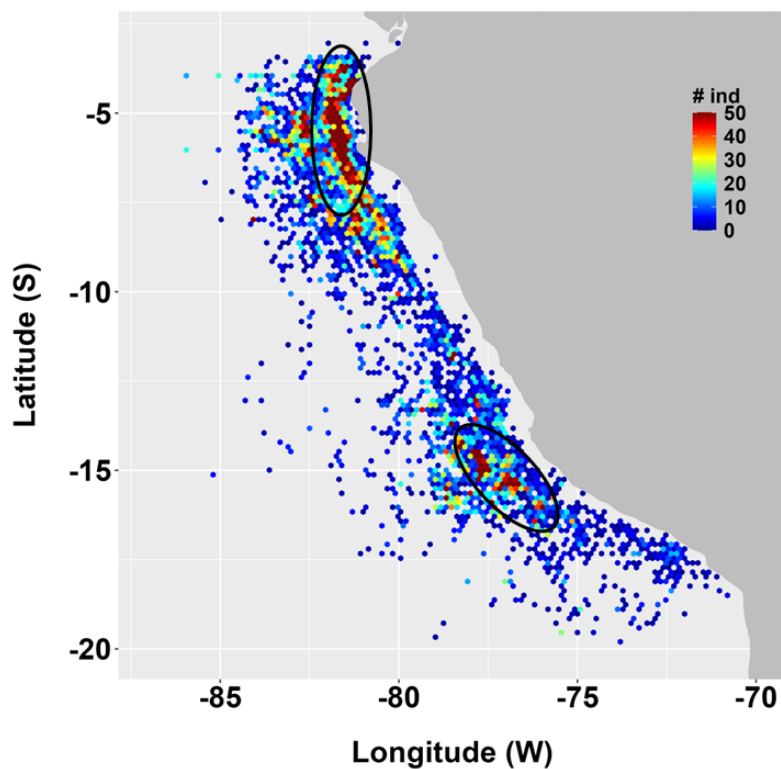


Fig. 2: Spatial distribution of mature females between the years 1989 and 2023. The black ellipses indicate areas of the two most important hotspots with the presence of mature females. The pixel size is 0.15° .

By segregating the spatial distribution of mature females according to size group (Fig. 3), we observed that small and medium-sized mature females were concentrated in the northern zone, while large mature females were significantly present in the southern zone as well. The area in central Peru is regarded as a diffuse zone, exhibiting a relatively diminished prevalence of mature females. Fig. 4 shows the initial spawning positions used as a starting point for paralarvae transport simulations based on the findings in Fig. 2.

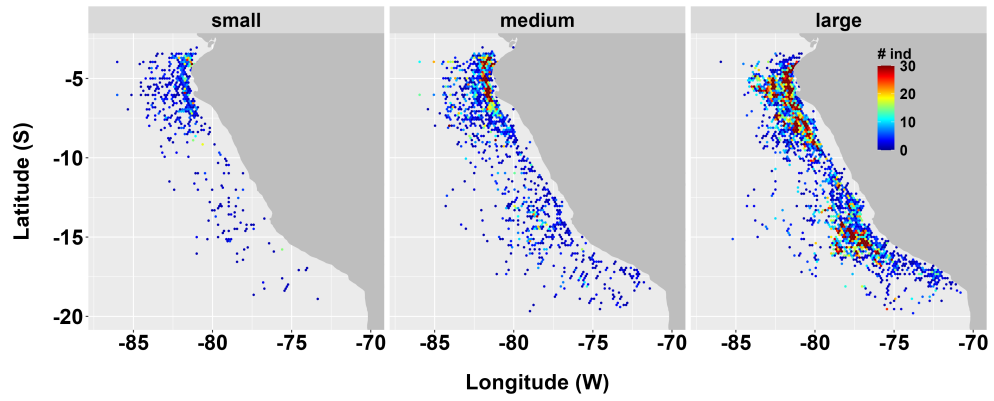


Fig. 3: Same as Fig. 2, but by morphotype.

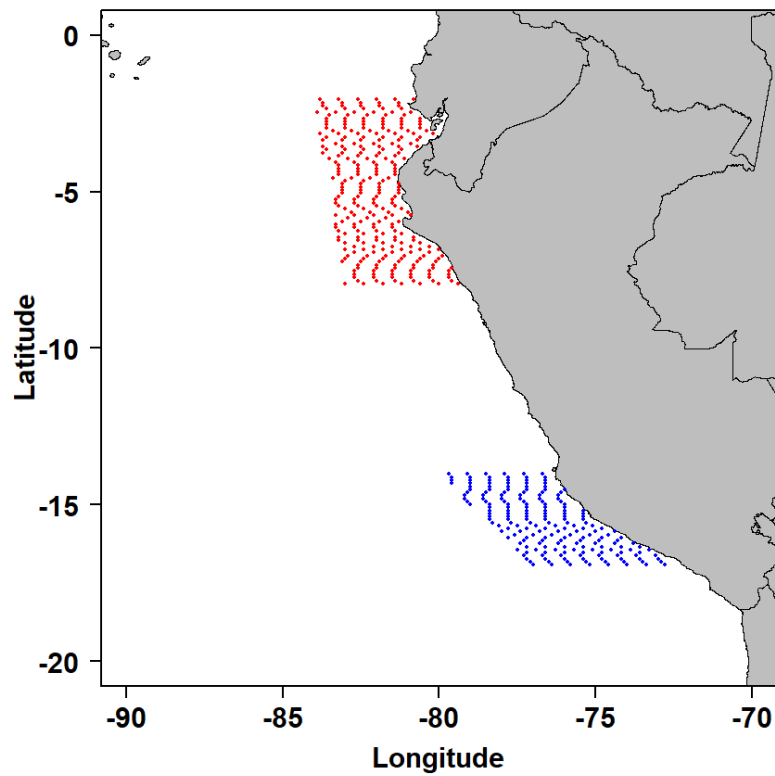


Fig. 4: Initial spawning position of *Dosidicus gigas* off the Peruvian coast. The red dots represent the northern area and the blue dots the southern area.

4.2 Paralarval drift experiments

Following a 30-day drift period, the simulated trajectories of the ELS of *D. gigas* in northern and southern Peru exhibited notable seasonal variability, with the northern zone displaying the most pronounced changes when particles were released at 5 m depth. During the months of June to October, it is feasible that trajectories may extend as far as the Galapagos Islands, contingent on the spawning of individuals in the northern region. It was possible to observe some deepening southward trajectories due to the subsurface countercurrent (Fig. 5). The southern area showed a lower degree of dispersion.

The degree of retention was found to be higher and similar in both northern and southern areas when individuals were spawned at a depth of 35 m. and exhibiting a deeper particle depth and failing to extend to distant areas such as the Galapagos, in contrast to the spawning depth of 5 metres (Fig. 6).

The dispersion of individuals was markedly greater in the northern region and during spawning in shallow layers (5 and 15 m). In the southern zone, the degree of dispersal was significantly lower, with an average distance of just over 200 km, and exhibited minimal variation with respect to spawning depth (Fig. 7).

The dispersion exhibited a discernible seasonal pattern exclusively in the northern region, with elevated means during the winter months. In the southern region, the mean dispersion distance remained relatively constant throughout the year (Fig. 8).

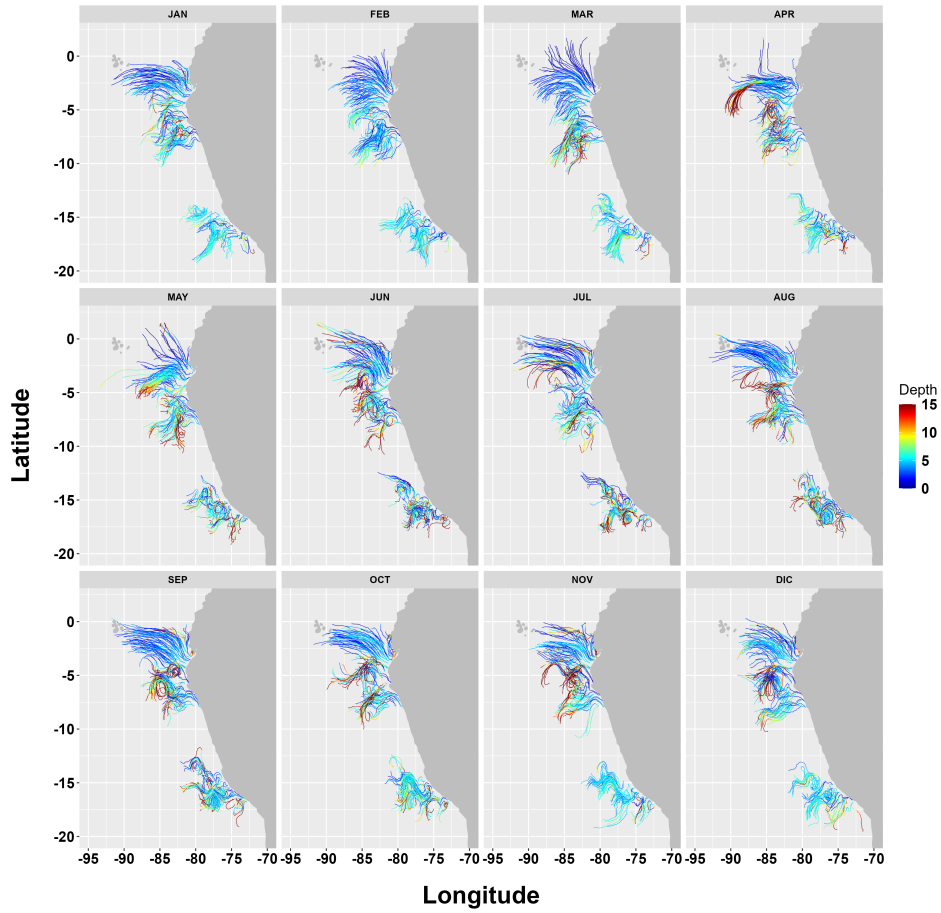


Fig. 5: Monthly trajectories of spawning individuals in northern and southern Peru spawned at a depth of 5 m. A sample of 500 individuals was taken.

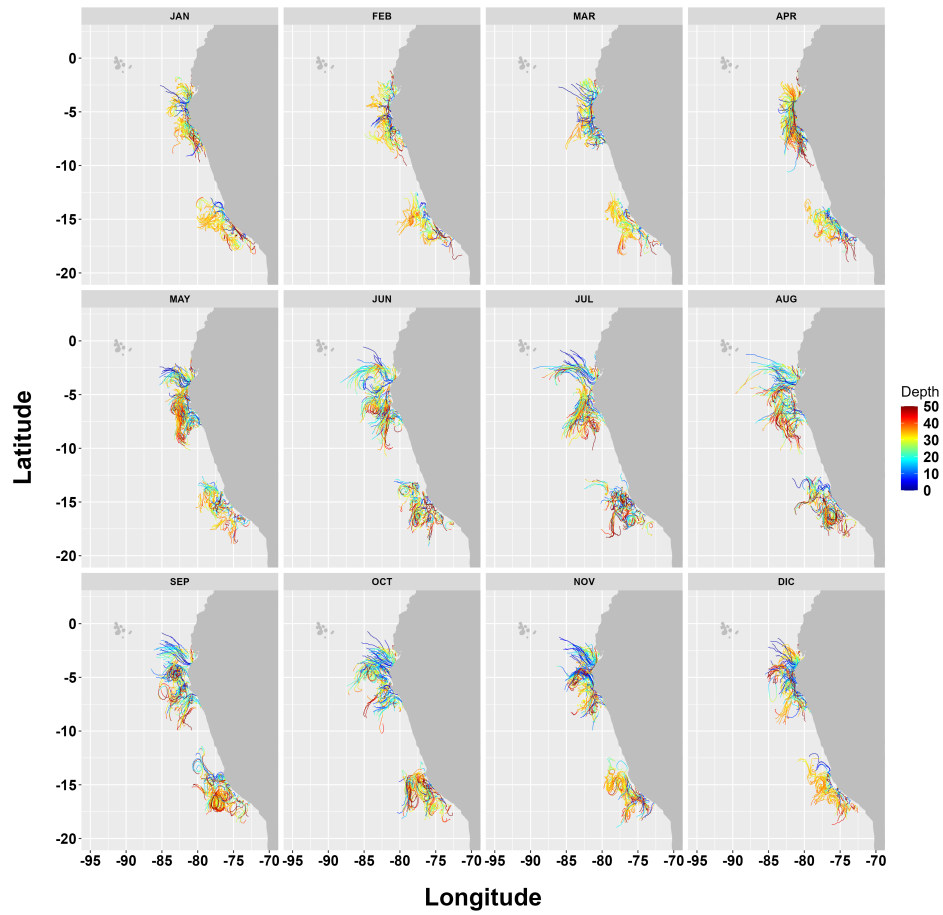


Fig. 6: Same as Fig. 5, but particles were released at 35 m.

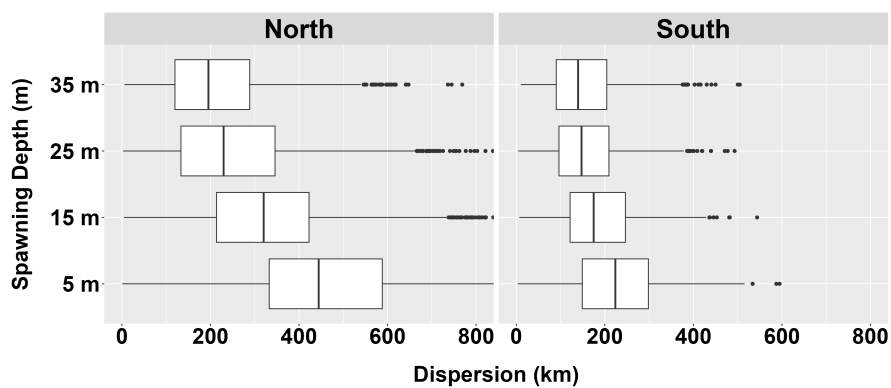


Fig. 7: Box plot of distance travelled (dispersion in km, X-axis) as a function of spawning depth (m, Y-axis) for individuals spawned in the northern and southern areas.

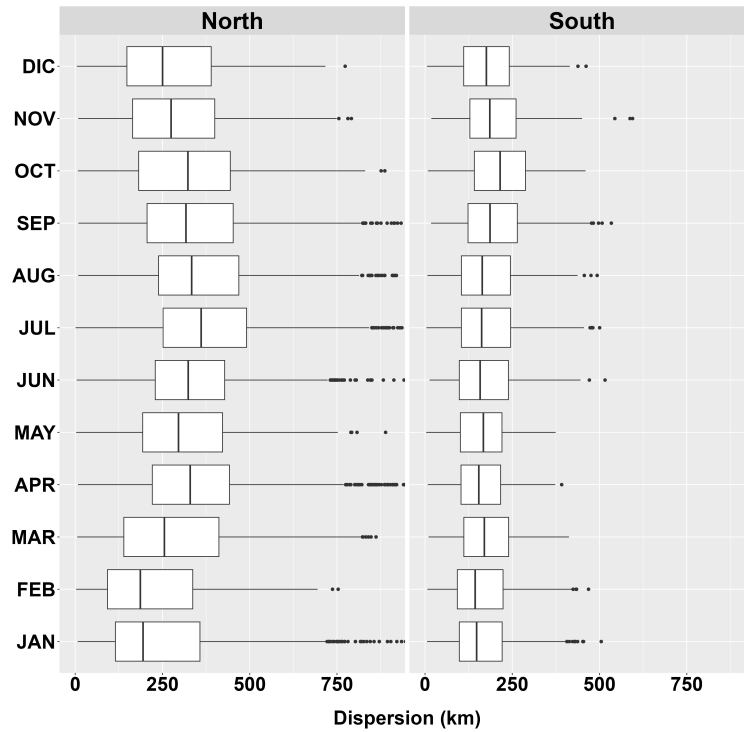


Fig. 8: Box plot of distance travelled (dispersion in km, X-axis) as a function of spawning month (m , Y-axis) for individuals spawned in the northern and southern areas.

5 Discussion and conclusions

The larval drift modelling approach has been successfully employed in the study of the ecology of other invertebrates as bivalves (Flores-Valiente *et al.*, 2019) and crustaceans (Peliz *et al.*, 2007) using ocean currents as forcing agents. A period of 30 days is typical for this type of study, although longer periods may be used, given the variable duration of the planktonic stage of *D. gigas*, especially its incubation period (Yatsu *et al.*, 1999). Nevertheless, to enhance the realism of these studies, it is advised that species-specific growth models be incorporated, as well as Flores-Valiente *et al.* (2023) for Peruvian anchovy.

The spatial scale of the study (10 km) is sufficient to describe the dispersal patterns of the jumbo flying squid, as it typically exhibits minimal presence in coastal areas and bays, where the current model's spatial resolution may be constrained, affecting retention patterns in very shallow (bays) areas (Arellano *et al.*, 2023).

The spatial range for mapping spawning areas is constrained by sampling coverage, given the expansive distribution of *D. gigas* outside 200 miles from the Peruvian coast. This encompasses regions where data are currently lacking, including its southern range off the coast of Chile. Nevertheless, an examination of the spawning patterns of small and medium-sized mature females of *D. gigas* in the Peruvian coastal region reveals that the northern area may experience a disadvantage in terms of reproductive success due to the loss of individuals heading west. This is in contrast to the southern area, where large mature females would be the primary source of paralarvae, as well as exhibiting a high retention rate.

The experiments are limited in that they consider only passive movement as a function of ocean currents. It is recommended that a more complex version of the model, called *Evol – DEB* (Brochier *et al.*, 2018), be used. This model includes a complete life cycle of individuals, is multigenerational, and includes different algorithms for active movement (swimming). *Evol – DEB* has been shown to reproduce migration patterns in fish from spawning zones to nursery areas, a trait that may be employed to evaluate the conceptual hypothesis of ontogenetic migration as described by Alegre *et al.* (2014).

Although these simulations are conducted on a seasonal time scale, it is recommended to perform an exercise with an interannual forcing, given that

almost decadal periods of size ranges of mature females have been observed (Fig. 9). For example, during the 1990s, average sizes of 30 *cm* were observed, while in the 2000s the average size increased to 75 *cm*, and currently in the 2010s we are going through another period of smaller sizes (50 *cm*). It is important to note that this pattern may be subject to bias due to its reliance on fishery monitoring data, which does not adhere to a uniform sampling strategy across the entirety of Peru's territorial waters.

It can be concluded that the size groups of mature females of *D. gigas* exhibit disparate distributions, with the small and medium-sized groups predominantly situated in the northern zone, while the large groups occupy both the northern and southern zones.

The dispersal patterns of the small and medium-sized mature females are likely to be significantly impacted in the northern zone, with a notable loss of paralarvae during winter months, when individuals are spawned in the surface layers. The larger females, which are also present in the southern region, serve as the primary source of paralarvae, contributing to the population in the northern zone, when spawning occurs at greater depths (deeper than 25 *m*).

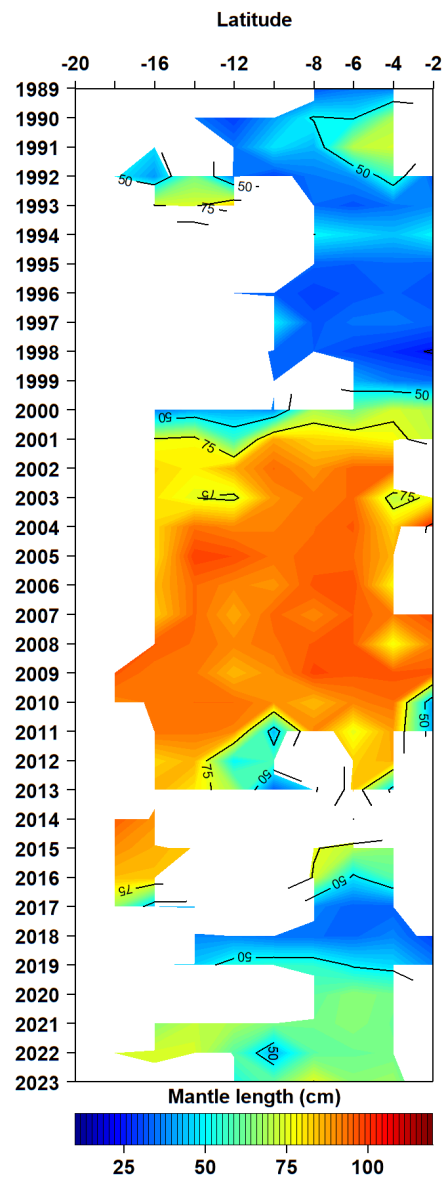


Fig. 9: Hovmoller diagram showing the average sizes (in cm) of mature females as a function of latitude (2-20 °S, X-axis) during the period 1989 to 2023 (Y-axis).

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Glossary

C

CROCO Coastal and Regional Ocean COmmunity model. [3](#), [4](#)

D

D. gigas Pelagic marine organism distributed in the Eastern Pacific Ocean from the US-Mexico border to Chile.. [1](#), [2](#), [3](#), [7](#), [11](#), [12](#)

E

ELS Early Life Stages. [1](#), [2](#), [3](#), [7](#)

I

IBM individual-based model. [3](#)

Ichthyop A Lagrangian tool for modelling ichthyoplankton dynamics. [3](#), [4](#)

IMARPE Instituto del Mar del Perú. [2](#)