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Identify habitat distribution within the mesoscale eddies for jumbo flying squid off Chilean waters

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Mesoscale eddies exert profound influences on marine environments, thereby regulating habitat quality and the distribution of marine organisms. The waters off Chile are a region of intense mesoscale eddy activity and represent a major habitat for the jumbo flying squid (*Dosidicus gigas*), a short-lived and economically important species. However, the effects of mesoscale eddies on the habitat of *D. gigas* in this region remain poorly understood. In this study, we integrated autumn (March–May) fisheries data of *D. gigas* from 2015 to 2021 with environmental variables, including sea surface temperature (SST), chlorophyll-a concentration (Chl-a), and sea surface dissolved oxygen concentration (DO), to develop and validate habitat suitability index (HSI) models with different weighting schemes. Using the optimal HSI model in combination with mesoscale eddy data, we compared the impacts of cyclonic and anticyclonic eddies on *D. gigas* abundance and habitat suitability. The results revealed that the optimal HSI model effectively predicted the potential habitats of *D. gigas*, with weights for SI_{DO} , SI_{SST} , and SI_{Chl-a} of 0.1, 0.1, and 0.8, respectively. Compared with anticyclonic eddies, cyclonic eddies provided broader areas of suitable habitats, characterized by suitable Chl-a and DO levels, and supported higher *D. gigas* abundances. Furthermore, the habitat suitability of *D. gigas* within mesoscale eddies exhibited interannual variability and was significantly correlated with the radius, velocity, and amplitude of the eddies. This study highlighted the critical role of mesoscale eddies in shaping the habitat suitability of *D. gigas* and provided valuable insights for the management and conservation of cephalopod resources.

KEYWORDS

Dosidicus gigas, mesoscale eddy, habitat assessment, abundance, the waters off Chile

1 Introduction

A habitat refers to the environment on which organisms depend for survival, growth, and reproduction (National Research Council, 1982). Different species have specific habitat requirements, and changes in habitat conditions can directly affect population dynamics. Therefore, analyzing and assessing habitat quality is essential for the conservation and management of biological populations. The habitat suitability index (HSI) model is a widely used approach to evaluate habitat quality and assess potential developmental impacts (Hightower et al., 2012). First proposed in the 1980s by the U.S. Geological Survey National Wetlands Research Center and Fish and Wildlife Department (Yu et al., 2015), the HSI model is valued for its simplicity, ease of interpretation, and robust performance. Its outputs can be integrated with geographic information systems (GIS), providing managers with practical decision-making tools (Vinagre et al., 2006). Today, HSI models have been extensively applied in evaluating habitats and predicting fishing grounds for marine cephalopods and fish species (Chen et al., 2009; Li et al., 2014; Tian et al., 2009). For instance, Wen et al. (2025) utilized an HSI model to analyze the effects of Indian Ocean Dipole (IOD) events on the habitat of *Sthenoteuthis oualaniensis*, revealing that negative IOD events resulted in more extensive suitable habitats compared to positive IOD phases.

The ocean encompasses dynamic processes across multiple spatial and temporal scales, among which mesoscale processes (approximately 50–500 km) represent a critical component (Covington et al., 2025), typically arising from oceanic instabilities (McGillicuddy, 2016). Mesoscale eddies, a key manifestation of these dynamics, are pervasive rotational structures that dominate the oceanic environment, accounting for a substantial portion of the ocean's total kinetic energy (Chelton et al., 2011; Wunsch and Ferrari, 2004). Generally, mesoscale eddies are classified into two types: cyclonic eddies (CEs), characterized by cooler water in their cores compared to the surrounding sea and thus referred to as cold eddies, and anticyclonic eddies (AEs), marked by warmer core waters and commonly termed warm eddies (Bakun, 2006). These eddies redistribute salinity, heat, and other substances, influencing general circulation, underwater sound propagation, and even the ocean's capacity for carbon dioxide absorption (Chelton et al., 2007; Li et al., 2025; Zhang et al., 2025). Moreover, they play significant roles in wind, clouds, rainfall, and marine heatwaves (Bian et al., 2023; Frenger et al., 2013; Ma et al., 2015). Importantly, mesoscale eddies are also recognized as critical drivers of habitat quality and the spatial distribution of marine organisms. For example, Davis et al. (2002) reported that CEs in the northern Gulf of Mexico serve as preferred foraging areas for cetaceans due to the aggregation of abundant prey, while Nieto et al. (2014) found that mesoscale eddies in the southern Gulf of California entrain suitable water masses, thereby creating suitable spawning habitats for sardines. These findings highlight the necessity of elucidating the influence and underlying mechanisms of mesoscale eddies on the habitats of diverse marine species to support sustainable fisheries management.

The jumbo flying squid (*Dosidicus gigas*), belonging to the family *Ommastrephidae*, is a highly valuable economic species

widely distributed east of 140°W (Chen et al., 2008). Compared to other members of *Ommastrephidae*, *D. gigas* is characterized by its large body size, thick flesh, rapid juvenile growth, and strong predatory capacity (Ibáñez et al., 2016; Nigmatullin, 2001). Notably, its population structure, dietary composition, and migratory patterns exhibit variation across different geographic regions (Ibáñez et al., 2016; Nigmatullin, 2001). The waters off Chile harbor abundant *D. gigas* resources; as early as the 1960s, Soviet fishing vessels reported massive aggregations of the species in these coastal areas (Yu et al., 2025). Today, this region remains one of the world's primary fishing grounds for *D. gigas*. Known for its high sensitivity to environmental variability, even minor changes in oceanographic conditions can lead to significant shifts in its habitat distribution (Yu et al., 2025). Feng et al. (2025) found that when sea surface height above geoid anomaly decreased and sea surface salinity and 400 m water layer temperature increased, the area of suitable habitat for *D. gigas* increased. The Chilean waters, situated within a boundary upwelling system, are an area with active mesoscale eddy activity (Chaigneau et al., 2009). Although previous studies have demonstrated the significant influence of mesoscale eddies on the habitat distribution of *Ommastrephidae* species (Alabia et al., 2015; Della Penna et al., 2022), research on how eddies affect the habitat of *D. gigas* in the Chilean region remains remarkably scarce.

To this end, this study developed an HSI model using *D. gigas* fisheries data and oceanographic environmental data from the waters off Chile and integrated mesoscale eddy datasets to analyze differences in the abundance and habitat distribution of *D. gigas* within CEs and AEs. The findings aim to provide a scientific basis for the conservation and sustainable utilization of *D. gigas* resources.

2 Materials and methods

2.1 Fisheries, environmental and mesoscale eddy data

From March to May during 2015–2021, *D. gigas* fisheries data were obtained from the National Distant-water Fisheries Data Center of China (NDFDC), Shanghai Ocean University, China. The fishing activities were conducted in the southeastern Pacific Ocean, covering the area between 70°–97°W and 20°–47°S. The dataset included information on fishing locations (longitude and latitude), fishing dates (year, month, day), catch (tons), and fishing effort (days). Catch per unit effort (CPUE, in unit of: t/d), calculated as the ratio of catch to fishing effort, was used as an indicator of *D. gigas* abundance.

A previous study (Wu et al., 2025) has shown that among the ten environmental factors, including sea surface height, sea surface salinity, and others, sea surface temperature (SST), chlorophyll-a concentration (Chl-a), and sea surface dissolved oxygen concentration (DO) are the environmental factors that have a significant impact on *D. gigas*. Consequently, this study focused on SST, Chl-a, and DO for subsequent analysis. SST data were

obtained from the global ocean physics reanalysis product provided by the Copernicus Marine Environment Monitoring Service (CMEMS) (https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_PHY_001_030/description), with a daily temporal resolution and a spatial resolution of 0.083°. Chl-a and DO data were sourced from the CMEMS global ocean biogeochemical hindcast product (https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_BGC_001_029/description), with a daily temporal resolution and a spatial resolution of 0.25°. The environmental datasets fully covered the spatial extent of the study area and were matched with the fisheries data for subsequent analyses.

The mesoscale eddy dataset used in this study was obtained from the eddy trajectory atlas product (META ver3.2), produced by SSALTO/DUACS and distributed by AVISO+ (<https://aviso.altimetry.fr>). This dataset identifies eddies based on absolute dynamic topography data with a spatial resolution of 0.25°, providing a more accurate representation of ocean dynamics in coastal regions, around islands, and in highly energetic areas (Pegliasco et al., 2022). We utilized the all-satellite version of this dataset, which includes daily information from January 2015 to December 2021 on the lifecycles, radius (unit: km), eddy center positions, velocity (unit: m/s), boundary contours, and amplitudes

(unit: m) of CEs and AEs within the study area. Figure 1 showed the spatial distribution of eddies in the study area on March 1, 2016.

2.2 Construction and validation of HSI model

This study incorporated fishing effort, SST, Chl-a, and DO into the HSI model. The process of constructing and validating the HSI model was as follows:

(1) Construction of the suitability index (SI) model. The observed SI was derived by calculating the ratio of fishing effort within a specific environmental variable classification interval to the maximum fishing effort within that interval (Yu et al., 2015). Based on previous studies and further testing (Feng et al., 2022, 2025; Jin et al., 2024a), the classification interval of SST was set to 0.5 °C for March, April, and May; that of Chl-a was 0.02, 0.03, and 0.02 mg/m³, respectively; and that of DO was 4, 2, and 3 mmol/m³, respectively. The observed SI values and classification intervals of each environmental variable were then used as input parameters to construct the fitted SI model according to the following equation (Wen et al., 2025):

$$SI_X = \exp[a \times (X - b)^2]$$

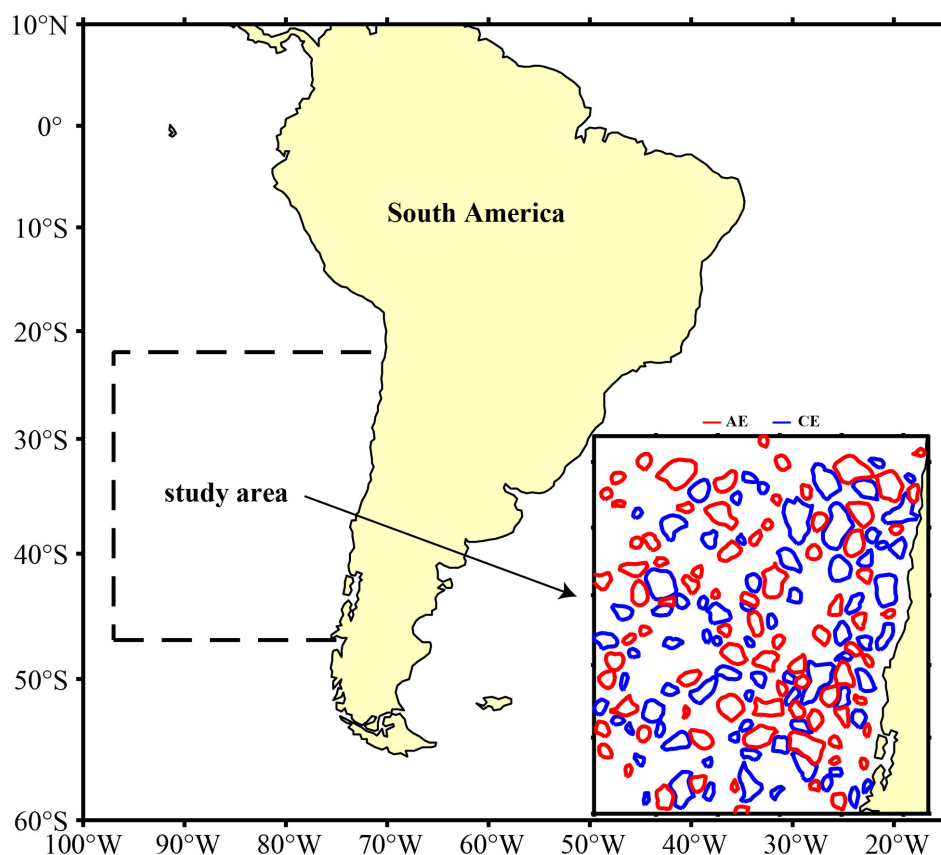


FIGURE 1

Spatial distribution of cyclonic and anticyclonic eddies on March 1, 2016 within the study area (blue lines were cyclonic eddies, red lines were anticyclonic eddies, and yellow areas were land).

where a and b were model parameters to be estimated; X was the classification interval values for each environmental variable.

(2) Assignment of model weights. Different weights (Supplementary Table S1) were assigned to the SI models of each environmental variable and then combined to construct the HSI model. The HSI model was calculated using the following equation:

$$HSI = \sum_{i=1}^n (SI_i \times M_i)$$

where M_i was the weight assigned to environmental variable i ; n was the total number of environmental variables included in the HSI model.

(3) Selection of the optimal model (a suboptimal solution within a limited parameter space). HSI values ranged from 0 to 1. Regions with $HSI \leq 0.2$, $0.2 < HSI < 0.6$, and $HSI \geq 0.6$ were classified as poor, moderate, and suitable habitats, respectively (Feng et al., 2022). Typically, in suitable habitats, the proportions of catch and fishing effort relative to their totals were greater, whereas the opposite trend was observed in poor habitats. Furthermore, as HSI increased, the proportions of catch and fishing effort also increased (Yu et al., 2015). Based on this theory, the optimal model was selected.

(4) Model validation. The HSI model was constructed using *D. gigas* fisheries and environmental data from 2015 to 2018. Habitat suitability for 2019–2021 was predicted and compared to actual *D. gigas* fisheries data to assess the model's performance.

2.3 Analysis of differences in the distribution of *D. gigas* habitat within CEs and AEs

This study defined the eddy influence range as twice its actual coverage area (Zhou et al., 2021). Given that eddies often exhibit irregular shapes, a standardized circular grid was applied to uniformly represent the daily influence range of each eddy. The radius of this standardized circular grid was $2R$, where R was the radius of the circle that best approximates the shape of the eddy's outermost closed contour (Pegliasco et al., 2022). This circular grid was further divided into two regions: the $0-R$ region, which was the inner circle from the center to R , and the $R-2R$ region, which was the annular zone extending from R to $2R$. Using daily *D. gigas* fishing location data and eddy boundary contours data, grids containing *D. gigas* fishing points were identified for each day, and the CPUE of *D. gigas* within grids of different eddy types was calculated. A t -test was then employed to compare the CPUE differences between CEs and AEs.

Based on the optimal HSI model described in Section 2.2, daily *D. gigas* HSI values were computed across the study area. The HSI values corresponding to circular eddy grids containing *D. gigas* fishing points were extracted, grouped by eddy polarity and year, and averaged to compare habitat quality between the two eddy types and to assess interannual variation. Furthermore, the study examined how the proportion of suitable habitat area within circular eddy grids varied with increasing distance from the eddy center.

2.4 Influence of eddy parameters on habitat suitability for *D. gigas*

This study employed a generalized additive model (GAM) to analyze the effects of eddy parameters on the habitat suitability of *D. gigas* within their influence ranges. The GAM, a nonparametric extension of the generalized linear model, was capable of describing nonlinear relationships between response and explanatory variables (Han et al., 2022). The GAM was constructed as follows:

$$g(Y) = \alpha + \sum_{i=1}^n f_i(x_i) + \varepsilon$$

where Y was the mean HSI of *D. gigas* within CEs or AEs; $g(\cdot)$ was the link function; α was the intercept; $f_i(\cdot)$ was the smooth function; x_i was eddy parameters (radius, velocity, and amplitude); ε was the random error.

Prior to GAM analysis, variance inflation factors (VIF) were calculated to test for multicollinearity among explanatory variables. The results indicated no significant multicollinearity ($VIF < 10$) (O'Brien, 2007). The GAM analyses were conducted in R (Version 4.4.0) using the "mgcv" (Version 1.9-1) package.

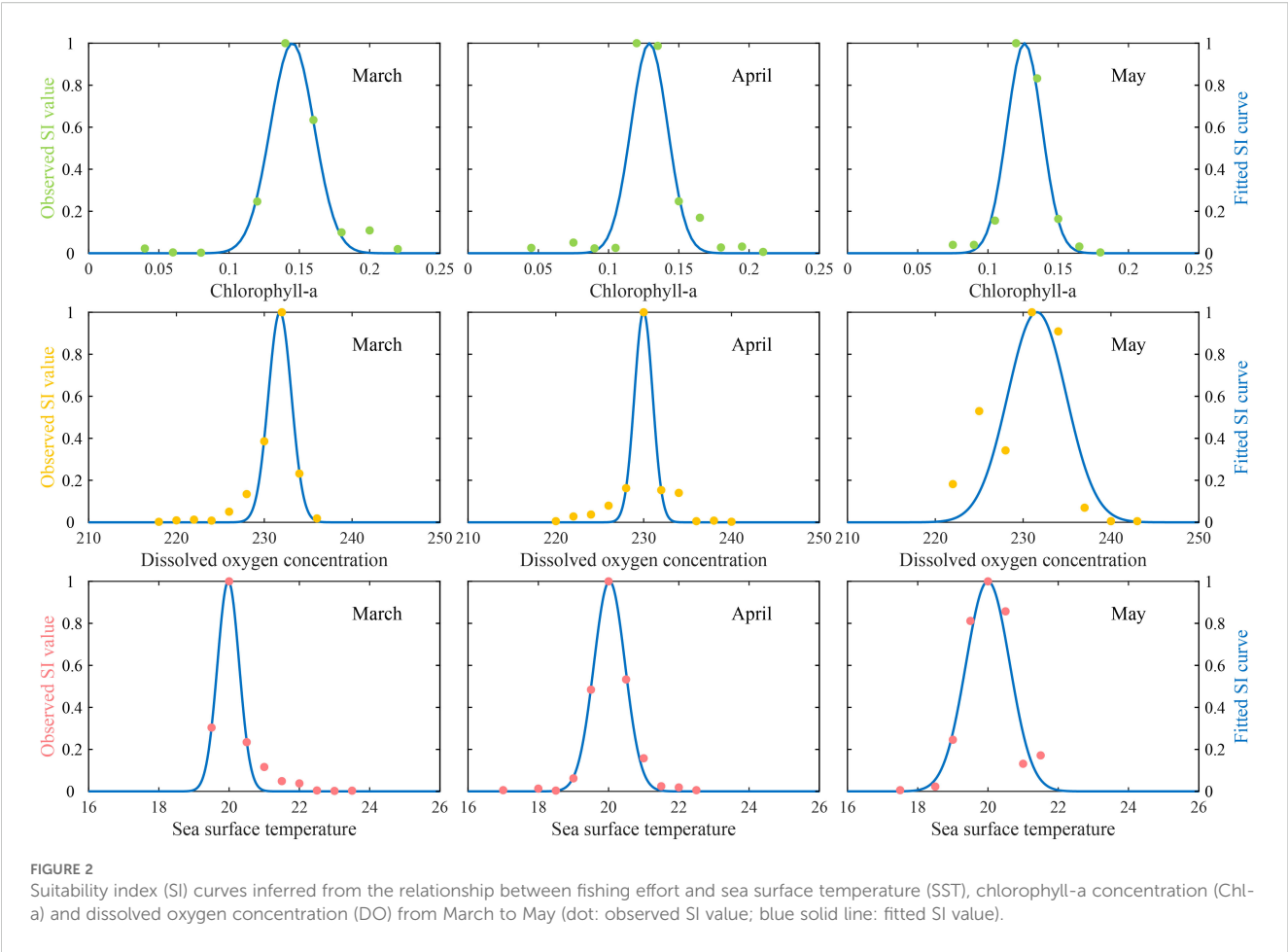
3 Results

3.1 HSI model results

The SI curves for SST, Chl-a, and DO, fitted using over 2000 *D. gigas* fishing points data collected from March to May 2015–2018 off Chile, were shown in Figure 2, and the corresponding SI model parameters were summarized in Table 1. All SI models were highly significant and demonstrated strong fits ($R^2 > 0.8$, $P < 0.001$). The fitted SI curves exhibited clear normal distributions and closely matched the observed SI values. The suitable environmental ranges within the *D. gigas* fishing grounds off Chile were approximately: March (SST: 19.59–20.37 °C; Chl-a: 0.13–0.16 mg/m³; DO: 230.02–233.55 mmol/m³), April (SST: 19.45–20.59 °C; Chl-a: 0.12–0.14 mg/m³; DO: 228.58–231.39 mmol/m³), and May (SST: 19.20–20.80 °C; Chl-a: 0.12–0.14 mg/m³; DO: 227.13–236.04 mmol/m³).

The percentage of catch and fishing effort in different HSI intervals under different weighting models was shown in Supplementary Table S2. The results indicated that case 6 had the highest proportions of catch and effort within suitable habitats. Additionally, catch proportion and fishing effort proportion all increased with rising HSI. Based on these findings, case 6 (with weights of 0.1, 0.8, and 0.1 for SST, Chl-a, and DO, respectively) was identified as the optimal model.

Using the optimal HSI model, *D. gigas* habitat suitability from March to May 2019–2021 off Chile was predicted. The distribution of observed CPUE across HSI intervals (at 0.2 increments) is illustrated in Figure 3. The results revealed that *D. gigas* CPUE was relatively high when $HSI > 0.6$, peaking at approximately 2.86 t/d within the 0.8–1.0 HSI interval, and relatively low when $HSI < 0.6$, with the lowest CPUE around 0.59 t/d in the 0.0–0.2 HSI interval.



3.2 The abundance of *D. gigas* within CEs and AEs

Figure 4 illustrated the distribution of *D. gigas* CPUE within different types of eddies. In AEs, the median CPUE was 2.7 t/d, with a mean value of 3.64 t/d. In CEs, the median CPUE was 3.6 t/d, and

the mean value was 4.26 t/d. The *t*-test results indicated that there was a significant difference in the CPUE of *D. gigas* within CEs and AEs ($P<0.001$).

3.3 Distribution of habitat suitability and its interannual variability for *D. gigas* in CEs and AEs

The distribution patterns of mean HSI, SI_{SST} , SI_{Chl-a} , and SI_{DO} within eddies of different polarities were shown in Figure 5A. In CEs, the mean SI_{DO} ranged from 0.32 to 0.58, while in AEs, it ranged from 0.26 to 0.45. The mean SI_{SST} did not exceed 0.6 in either CEs or AEs. Both the number of grids with mean HSI and mean SI_{Chl-a} greater than 0.6 were higher in CEs compared to AEs.

The mean HSI, SI_{SST} , SI_{Chl-a} , and SI_{DO} in different eddy regions were presented in Figure 5B. In the 0-R region, CEs exhibited significantly higher HSI, SI_{Chl-a} ($P<0.05$), and SI_{DO} than AEs, while the SI_{SST} was significantly lower ($P<0.05$). In the R-2R region, there was not a significant difference between the two eddy types in the HSI and SI_{Chl-a} ($P>0.05$); however, CEs exhibited a significantly lower SI_{SST} and a higher SI_{DO} than AEs ($P<0.05$).

Figure 6 showed the relationship between the proportion of suitable HSI and the distance from the eddy center. Overall, the proportion of suitable HSI decreased with increasing distance from

Month	SI model for each environmental variable	R ²	P
March	$SI_{Chl-a}=\exp[-2071.857(X_{Chl-a}-0.145)^2]$	0.984	<0.001
	$SI_{DO}=\exp[-0.289(X_{DO}-231.784)^2]$	0.98	<0.001
	$SI_{SST}=\exp[-5.214(X_{SST}-19.977)^2]$	0.98	<0.001
April	$SI_{Chl-a}=\exp[-2945.822(X_{Chl-a}-0.129)^2]$	0.928	<0.001
	$SI_{DO}=\exp[-0.459(X_{DO}-229.985)^2]$	0.967	<0.001
	$SI_{SST}=\exp[-2.544(X_{SST}-20.027)^2]$	0.993	<0.001
May	$SI_{Chl-a}=\exp[-3227.451(X_{Chl-a}-0.126)^2]$	0.977	<0.001
	$SI_{DO}=\exp[-0.045(X_{DO}-231.583)^2]$	0.842	<0.001
	$SI_{SST}=\exp[-1.280(X_{SST}-19.998)^2]$	0.954	<0.001

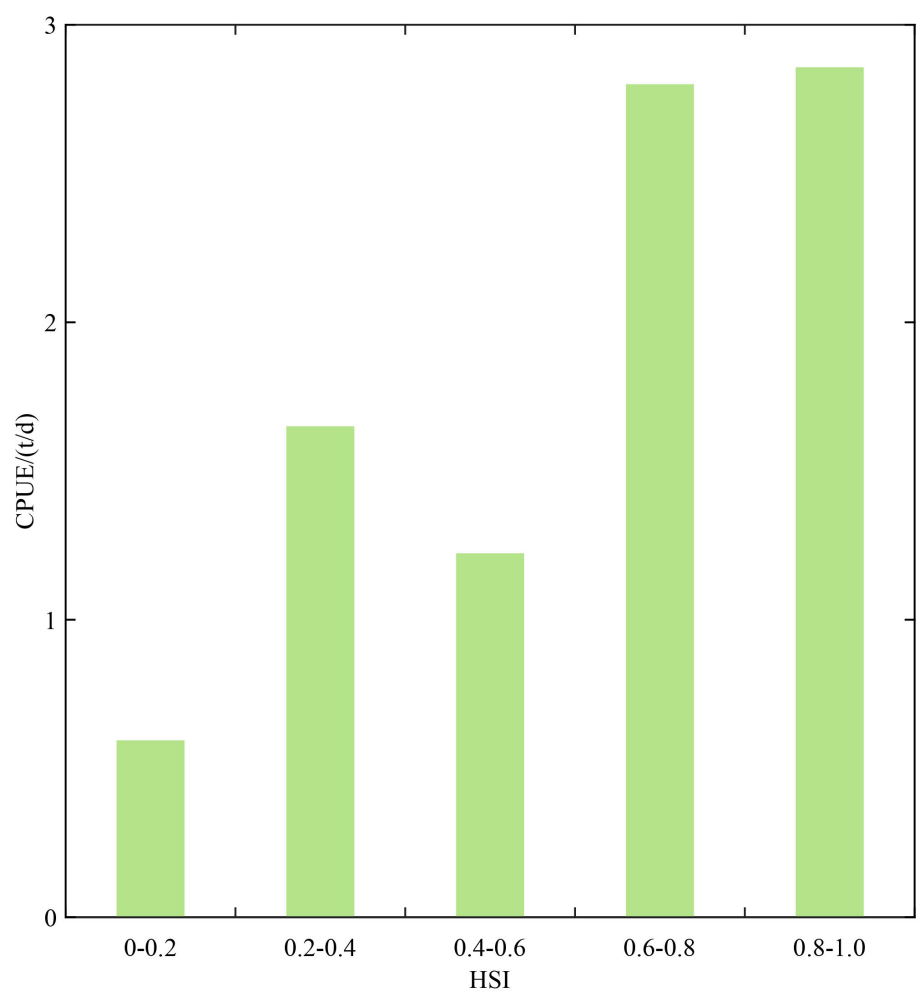


FIGURE 3
Mean catch per unit effort (CPUE) corresponding to each interval of habitat suitability index (HSI) under the optimal HSI model (case 6) from 2019 to 2021.

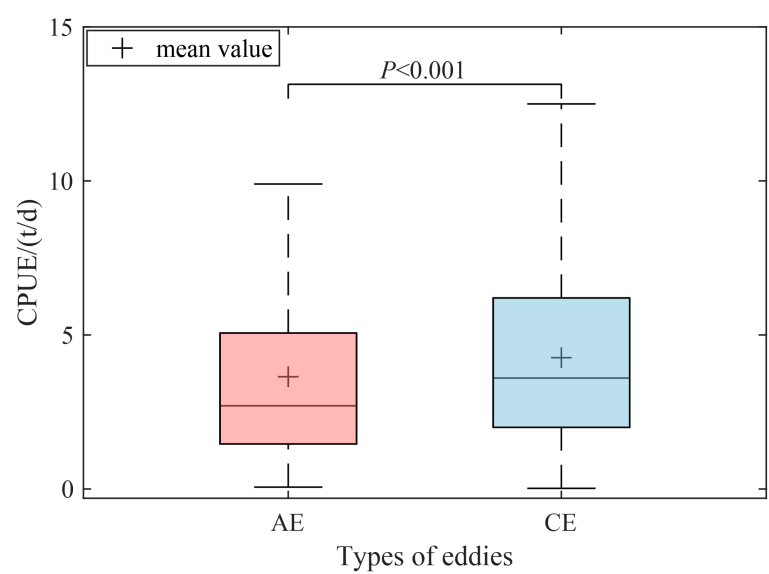


FIGURE 4
Comparison of catch per unit effort (CPUE) between anticyclonic (AE) and cyclonic eddy (CE).

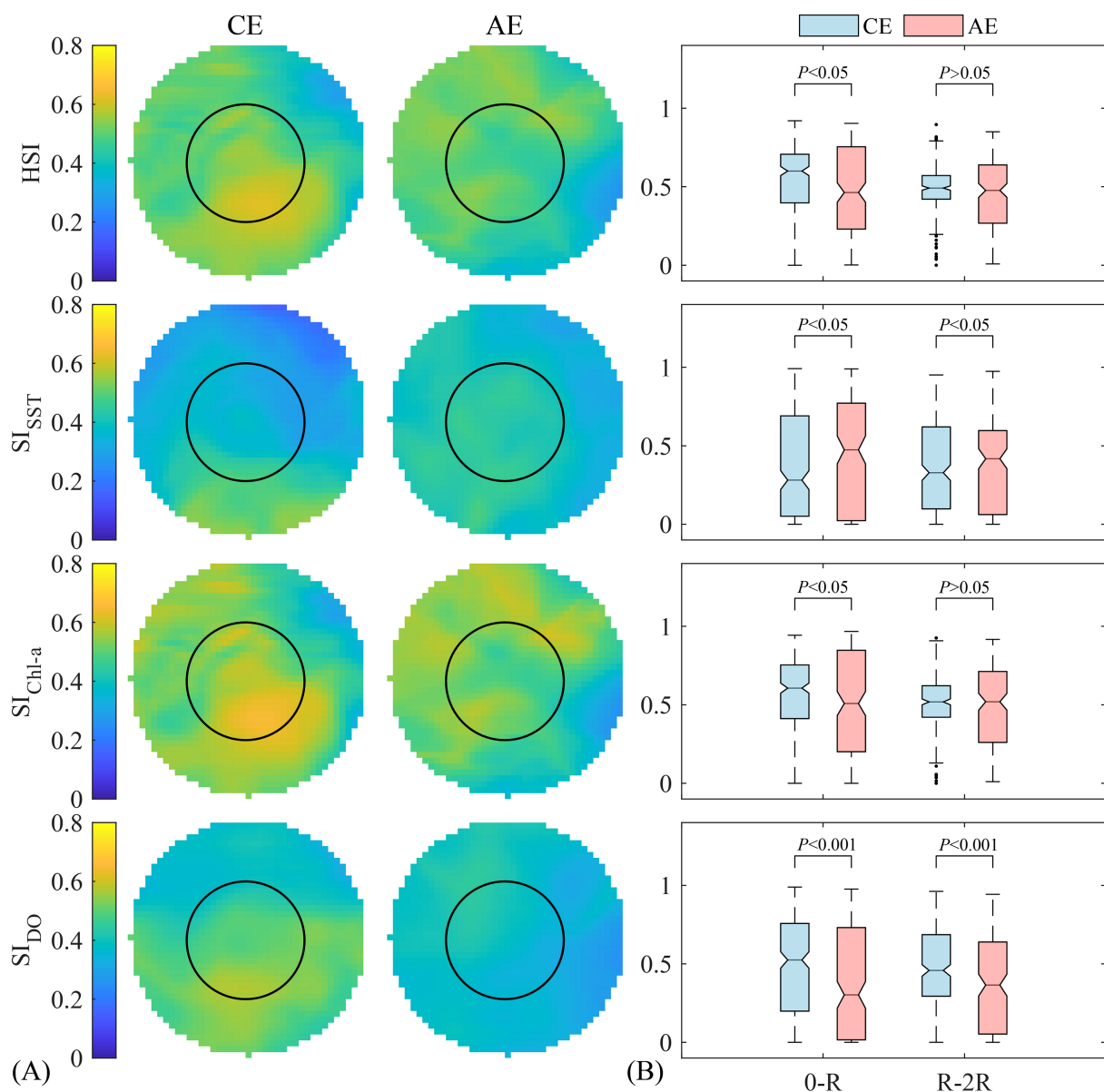


FIGURE 5

(A) Comparison of the average suitability index values for each environmental factor and the average habitat suitability index (HSI) for *Dosidicus gigas* between cyclonic (CE) and anticyclonic eddy (AE) (the black solid line represents the inner circle from the center to R); (B) Boxplot comparison of the mean habitat suitability index (HSI) and single-factor suitability index (SI) in different regions of the eddies (the 0-R region is the inner circle from the center to R, the R-2R region is the annular zone extending from R to 2R, R is half the radius of the standardized circular grid).

the eddy core in both CEs and AEs. In CEs, the proportion peaked at 57.5% (0.1 R) and dropped to 44.8% (2.0 R), while in AEs, the highest proportion was 51.3% (0.6 R) and the lowest was 41.7% (1.9 R).

Differences in *D. gigas* habitat suitability between the two eddy types from 2015 to 2020 are depicted in Figure 7. Overall, HSI values in both CEs and AEs exhibited notable interannual variability. In most years, the core regions of CEs showed relatively high HSI values, especially in 2019 and 2020. In 2016, 2017, and 2020, AEs also displayed relatively high HSI values. However, in 2018, habitat suitability was relatively poor within both eddy types.

3.4 Influence of eddy parameters on habitat suitability for *D. gigas*

The deviance explained by the GAM model constructed based on AE data was 41.3%, whereas the deviance explained by the GAM model constructed based on CE data was 30.9%. The GAM results revealed that radius, velocity, and amplitude all exerted significant effects on the habitat suitability of *D. gigas* (Figure 8). When the radius of CEs ranged from approximately 50 to 125 km, the confidence interval was relatively narrow, and the HSI increased with the radius. In contrast, for AEs, when the radius was approximately 45 to 60 km, the confidence interval was narrower,

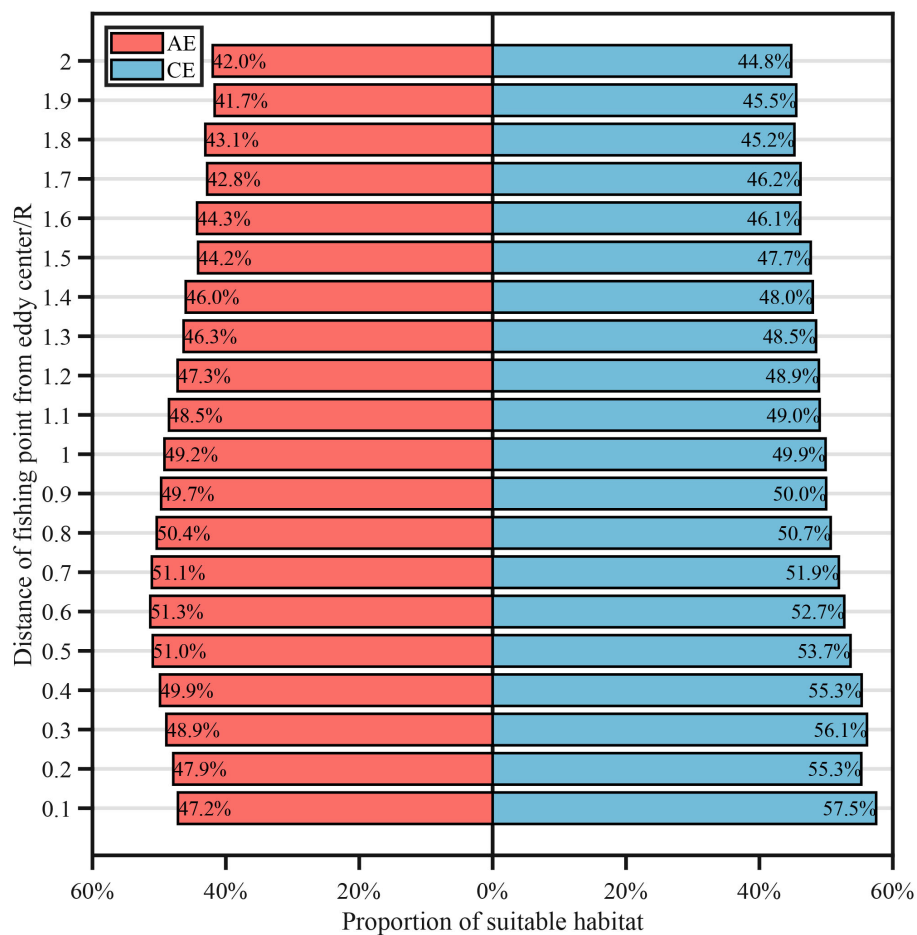


FIGURE 6

Proportion of suitable habitat in cyclonic (CE) and anticyclonic eddy (AE) at varying distances from eddies centers.

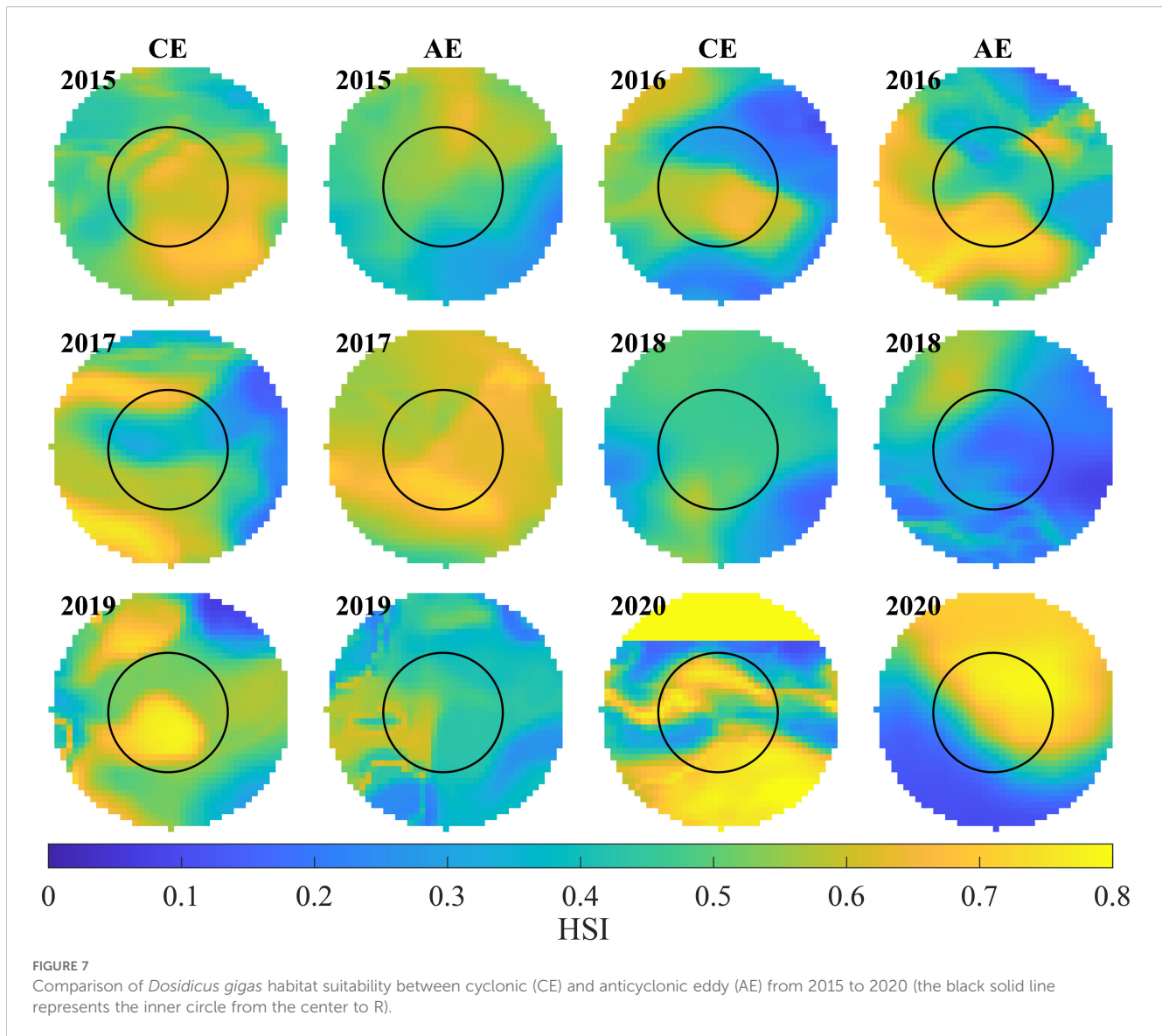
and the HSI decreased as the radius increased. In CEs, HSI increased with rising velocity, peaking at approximately 0.15 m/s before gradually declining. Conversely, in AEs, HSI tended to mainly decrease as rotational speed increased. Regarding amplitude, HSI in AEs first increased and then declined as amplitude increased, whereas in CEs, HSI progressively decreased as amplitude increased.

4 Discussion

Habitat quality directly influences the presence and abundance of marine organisms. Understanding the spatial and temporal dynamics of habitats is critical for sustaining biological resources. Numerous models have been developed to identify and predict marine species' habitat distributions, such as the MaxEnt model (Jones et al., 2012), neural network models (Lin et al., 2023), and generalized additive mixed models (Wang et al., 2023). Compared to these, the HSI model is valued for its simplicity, transparency, speed, and reliability, and it has been widely applied in wildlife management (Li et al., 2014). In this study, squid fishing effort data and environmental variables were used as inputs to construct the HSI model. A previous study on Pacific squid demonstrated that

HSI models based on CPUE tend to incorrectly estimate suitable habitat areas and their monthly variability compared to those constructed using fishing effort (Tian et al., 2009). The structure of the HSI model also plays a decisive role in its predictive accuracy. Various methods exist to combine individual SI models into an overall HSI, such as multiplicative, hybrid, geometric mean, and arithmetic mean approaches (Gong et al., 2011). Each approach yields different HSI values. Although the geometric and arithmetic means are commonly used (Tian et al., 2009; Yu et al., 2015), they assume equal species responses to all environmental factors and may fail to accurately capture habitat suitability. To address this limitation, this study applied 25 different weighting schemes (Supplementary Table S1) for the SI model, evaluated their performance, and selected the optimal configuration for predicting *D. gigas* habitat suitability.

In this study, the constructed SI models exhibited a clear normal distribution ($P < 0.001$) (Table 1) and showed strong consistency with the observed SI values (Figure 2), indicating that the models effectively quantified the suitability of *D. gigas* in relation to the selected environmental variables. Moreover, we observed monthly fluctuations in the suitable ranges of DO, SST, and Chl-a for *D. gigas*, which aligns with findings from previous studies (Wen et al.,



2024; Yu et al., 2015). These variations reflect that the *D. gigas* are at different life history stages in different months and differ in their needs for the three environmental factors. DO, SST, and Chl-a represent metabolic constraints, thermal conditions, and food availability, respectively, and exert significant influences on the spatial distribution of *D. gigas* (Yu et al., 2025). The optimal weighting scheme for SI_{DO} , SI_{SST} , and SI_{Chl-a} was determined to be 0.1:0.1:0.8 (Supplementary Table S2), highlighting the dominant role of Chl-a in shaping *D. gigas* habitats during March–May. This period corresponds to one of the key spawning seasons of *D. gigas* off Chile (Ibáñez et al., 2016), during which their energy demands rely heavily on feeding (Yu et al., 2025). Given the potential positive relationship between Chl-a and the foraging environment of *D. gigas* (Ichii et al., 2002), the higher weight assigned to SI_{Chl-a} in our model appears justified. In contrast, a previous study (Wen et al., 2024) found that SST contributed more to *D. gigas* habitat formation than Chl-a in the eastern equatorial Pacific during the same season, suggesting that habitat formation mechanisms for the

same species may vary across different regions. The HSI model validation results (Figure 3) further demonstrated that *D. gigas* were predominantly distributed within areas classified as suitable habitats, underscoring the model's high predictive accuracy.

Mesoscale eddies profoundly influence the distribution of organisms across different trophic levels in marine food webs (Ueno et al., 2023). Owing to the contrasting current structures within CEs and AEs, various marine species exhibit distinct aggregation preferences in these eddies, and such patterns are often modulated by geographic location (Xing et al., 2023, 2024). For instance, compared to CEs, blue marlin, albacore tuna, blue sharks, and king penguins are more frequently observed aggregating within AEs (Arostegui et al., 2022; Braun et al., 2019; Cotté et al., 2007). In this study, however, analysis of multi-year autumn catch data for *D. gigas* off Chile, combined with mesoscale eddy datasets, revealed that CEs supported higher abundances of *D. gigas* relative to AEs (Figure 4). CEs promote upwelling and AEs induce downwelling in both hemispheres—the direction of rotation is

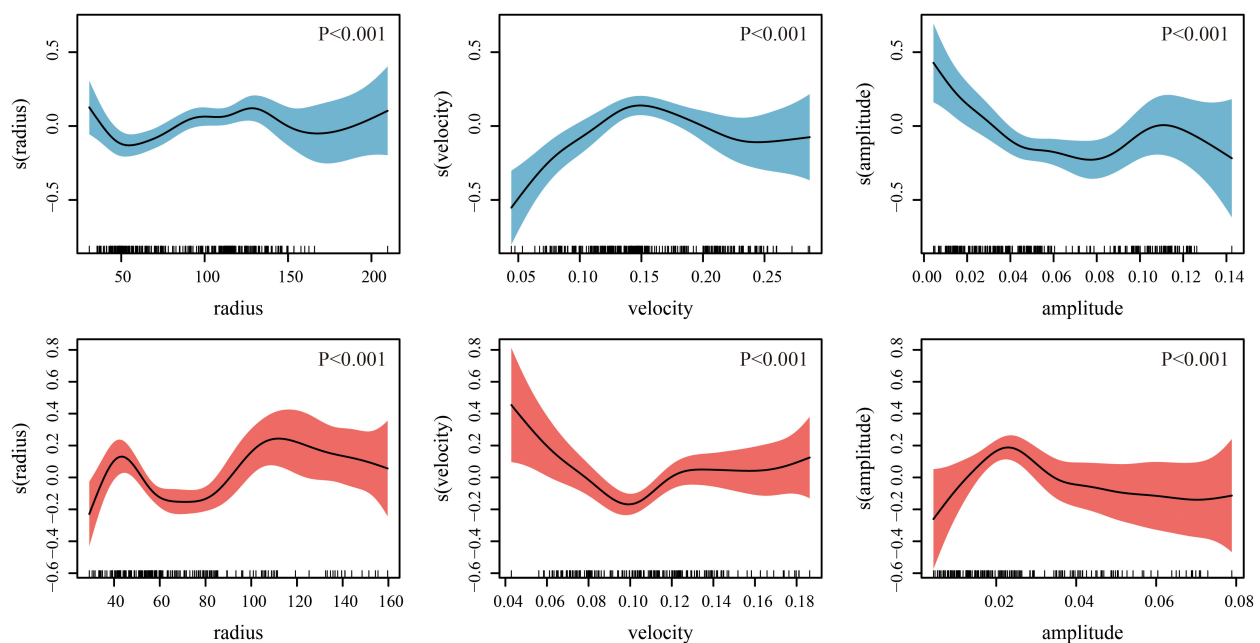


FIGURE 8

The influence of eddy parameters on the mean habitat suitability index (HSI) of *Dosidicus gigas* within their impact range (lower panel, anticyclonic eddies; upper panel, cyclonic eddies).

reversed between them. In the Southern Hemisphere, CEs rotate clockwise and AEs counter-clockwise, whereas in the Northern Hemisphere, the opposite occurs. These opposing dynamics distinctly modulate local DO, SST, and Chl-a conditions (Bakun, 2006), thereby creating habitat environments of differing quality within their influence zones. A comparison of *D. gigas* suitability for DO, SST, and Chl-a within the two eddy types (Figure 5) showed that CEs had a higher proportion of suitable $SI_{\text{Chl-a}}$ and SI_{DO} , while SI_{SST} proportions were slightly lower than in AEs. The combined effects of these three factors suggest that CEs provide more favorable habitats for *D. gigas*. Previous studies have also documented interannual variability in *D. gigas* habitat suitability within eddies (Jin et al., 2024b) and reported that the proportion of suitable habitats changes with distance from the eddy core (Jin et al., 2024a). Similar patterns were observed in our analysis (Figures 6, 7), likely driven by interannual fluctuations in oceanic conditions and energy differences across eddy regions. Eddy amplitude typically reflects its intensity, radius indicates its area of influence, and velocity reflects energy distribution and developmental dynamics (Cui et al., 2025). This study found that the quality of *D. gigas* habitats within eddies was significantly influenced by eddy radius, velocity, and amplitude (Figure 8). For example, the HSI within CEs was higher when the velocity was approximately 0.15 m/s, while HSI within AEs was lower when the velocity was around 0.10 m/s. The study hypothesizes that variations in eddy parameters may alter the distribution of water masses and the material transport capacity within the eddy, thereby driving changes in environmental factors and influencing the habitat suitability for *D. gigas*.

This study employed HSI models with varying weightings to investigate differences in the abundance and habitat of *D. gigas*

within CEs and AE off Chile during austral autumn. The results revealed that, compared to AEs, the suitable DO and Chl-a conditions within CEs facilitated the formation of high-quality habitats for *D. gigas*, leading to substantial aggregations of this species. However, the study has certain limitations. It did not account for the direct effects of upwelling and downwelling within mesoscale eddies on *D. gigas*, nor did it explore the mechanisms of eddy parameter effects on habitat suitability for *D. gigas* or consider the impacts of climate change on both eddies and squid populations. Future research should incorporate additional physical, biological, and climatic factors, along with more advanced models, such as convolutional neural networks, to explore species distribution changes driven by eddy-induced environmental factors. Overall, these findings offer novel insights into the ecological effects of mesoscale eddies on cephalopod species and provide a scientific basis for their sustainable management.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Ethics statement

The manuscript presents research on animals that do not require ethical approval for their study.

Author contributions

XW: Conceptualization, Formal Analysis, Methodology, Visualization, Writing – original draft. PJ: Conceptualization, Writing – original draft. WY: Conceptualization, Funding acquisition, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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