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LETTER

# Westerly winds prompted an anomalous southward migration of Pacific saury (*Cololabis saira*)

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## Scientific Significance Statement

Pacific saury is an important pelagic fish species in the Northwest Pacific. It undergoes southward migrations during autumn that coincide with peak fishing activity. Accurate prediction of its spatiotemporal distribution is crucial for both fishery operations and sustainable management. However, current forecasting capabilities remain constrained by insufficient understanding of high-frequency ocean variations and subsurface environment conditions. We break through these gaps by integrating continuous subsurface observations from mooring and synoptic wind effects. Our analysis reveals that westerly winds are favorable for the aggregation of Pacific saury. These findings underscore the critical importance of high-frequency environmental influences and continuous subsurface observation on fishery prediction and management.

## Abstract

The Pacific saury (*Cololabis saira*), a key pelagic fish in the Northwest Pacific, exhibits autumn migration modulated by Kuroshio–Oyashio Extension mesoscale features, yet daily fishing ground variability remains unexplained. Traditional reliance on remote sensing data has limited understanding of the three-dimensional mechanisms governing the fishing patterns. Through integration of continuous mooring observations with satellite data, we reveal how multi-scale oceanic processes drove an anomalous southward shift of Pacific saury in November 2016. Key findings demonstrate that: (1) Anticyclonic eddies enhanced the Oyashio intrusion, shaping the corridor for the southern fishing grounds; (2) Synoptic winds better explained the daily fishing vessel distributions than chlorophyll-*a*; (3) Westerly winds enhanced Pacific saury's feeding conditions by intensifying cold tongue–eddy interaction through Ekman transport. This study underscores the importance of synoptic-scale winds and continuous subsurface observations in understanding the three-dimensional evolution mechanisms of fishing ground, advocating for expanded mooring establishment for sustainable management.

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The Kuroshio–Oyashio Extension (KOE) region represents a dynamic mixing zone where the warm, saline Kuroshio Current meets the cold, nutrient-rich Oyashio Current (Hanawa and Sugimoto 2011; Inoue et al. 2003; Kono 1998; Mitsudera et al. 2004), creating sharp thermohaline gradients that structure one of the most biologically productive areas in the Northwest Pacific (Supporting Information Fig. S1). This confluence generates multi-scale physical features (Qiu et al. 2017; Jing et al. 2019), including mesoscale eddies, frontal systems, and wind-driven processes that collectively regulate nutrient fluxes and prey availability, making the KOE a critical habitat for pelagic fishes (Sakurai 2007) such as Pacific saury (*Cololabis saira*), which is commercially and ecologically important and sensitive to change in environmental conditions (Tian et al. 2003).

Pacific saury migrates southwards through the KOE every autumn, marking the peak fishing season (Huang 2009). Its distribution is governed by thermohaline preferences and zooplankton availability (Sugisaki and Kurita 2004; Huang and Huang 2015), both modulated by the local multi-scale oceanic features. For instance, the energetic and long-lasting (weeks to months) mesoscale eddies (Chaigneau et al. 2009; Chelton et al. 2011; Ueno et al. 2023) can enhance primary productivity (Bakun 2006; Gruber et al. 2011; Uchida et al. 2020; Xing et al. 2024b) and modify Pacific saury migration pathways via cold water entrainment along their peripheries (Saitoh et al. 1986; Sugimoto and Tameishi 1992). Similarly, Oyashio intrusions can generate cold, productive tongues (Qiu 2001) that shift Pacific saury aggregations shoreward (Yasuda and Watanabe 1994; Liu et al. 2022).

While Pacific saury distributions exhibit characteristic monthly-scale patterns tied to mesoscale features (Tseng et al. 2014; Xing et al. 2022), significant daily variability in fishing conditions (Tian et al. 2022) persists, a phenomenon mesoscale processes alone cannot explain. This gap highlights the critical role of higher-frequency physical–biological interactions. Synoptic-scale winds may play a vital role since the synergistic effects of mesoscale eddies and fronts can generate substantial eddy–atmosphere interactions (Combes and Matano 2018; Frenger et al. 2013). Synoptic winds can modulate the Ekman transport and wind stress curl, as well as Ekman pumping, mixing rates, and stratification (Brannigan 2016; Jacox and Edwards 2011; Largier et al. 2006), which can not only affect ocean primary production but also cause some potential effect on fisheries (Bakun et al. 2010; Schilling et al. 2021; Arteaga et al. 2024). However, current understanding of fishing ground formation relies heavily on satellite-derived surface data, which cannot resolve subsurface biophysical coupling. Subsurface mooring observation can address this gap by providing continuous, depth-resolved measurements of both physical and biological variables (Yang et al. 2022). Nevertheless, the high cost of deployment and a sparse network of stations limit their spatial coverage compared to remote sensing. This study, by demonstrating the critical insights gained from mooring observations, underscores the need to expand mooring networks for a more comprehensive, three-dimensional understanding of fishing ground evolution mechanisms.

During autumn, Pacific saury fishing activities in the open sea typically move from northeast to southwest along the eastern side of Japan's Exclusive Economic Zone (EEZ), generally remaining north of 40°N (Hung et al. 2023) (Fig. 1b,c). However, November 2016 marked a pronounced anomaly, as the fishing distribution shifted anomalously southward, with concentrations occurring south of 40°N (Fig. 1a)—a deviation potentially linked to mesoscale processes within the KOE region. Furthermore, daily variations in fishing activities during this month exceeded those associated with mesoscale features, implicating higher-frequency synoptic oceanic and atmospheric dynamics often overlooked in habitat studies. Understanding the mechanisms driving this southward shift and daily variation is critical for both elucidating fishing ground formation and improving predictive capabilities for this economically important species. Therefore, we carried out this research by integrating satellite remote sensing data with high-resolution subsurface mooring observation to demonstrate the comprehensive influence of multi-scale ocean processes on Pacific saury and underscore the necessity of incorporating vertical habitat structure and high-resolution physical–biological coupling into fishery oceanography.

## Materials and methods

### Fishery data

Pacific saury undergoes vertical migration, aligned with their zooplankton prey (Sugisaki and Kurita 2004). Their spatial distribution was reconstructed using the night-light fishing vessel data. Despite the absence of direct fishery yield data, it has been extensively and successfully employed in previous fishery research due to its high spatiotemporal resolution (Liu et al. 2015; Waluda et al. 2002, 2004). In November 2016, we identified 1531 fishing locations from night-light fishing vessels, which operate exclusively at night. Each recorded location includes corresponding positional coordinates and date. These locations have been validated and improved through comparison with Automatic Identification System (AIS) data, as demonstrated in previous studies (Tian et al. 2022).

### Environmental data

In April 2016, the M2 subsurface mooring (39°N, 150°E) was deployed in the KOE. It was equipped with two 75 kHz acoustic Doppler current profilers (ADCP, Workhorse Long Ranger, Teledyne RD Instruments) at 500 m depth (one upward-, one downward-facing), four conductivity temperature depth (CTD) (depths: 100, 400, 1500, 5500 m), and five temperature loggers in the upper 600 m. This configuration enabled continuous monitoring of temperature, current velocity and subsurface volumetric backscattering strength ($S_v$)—an

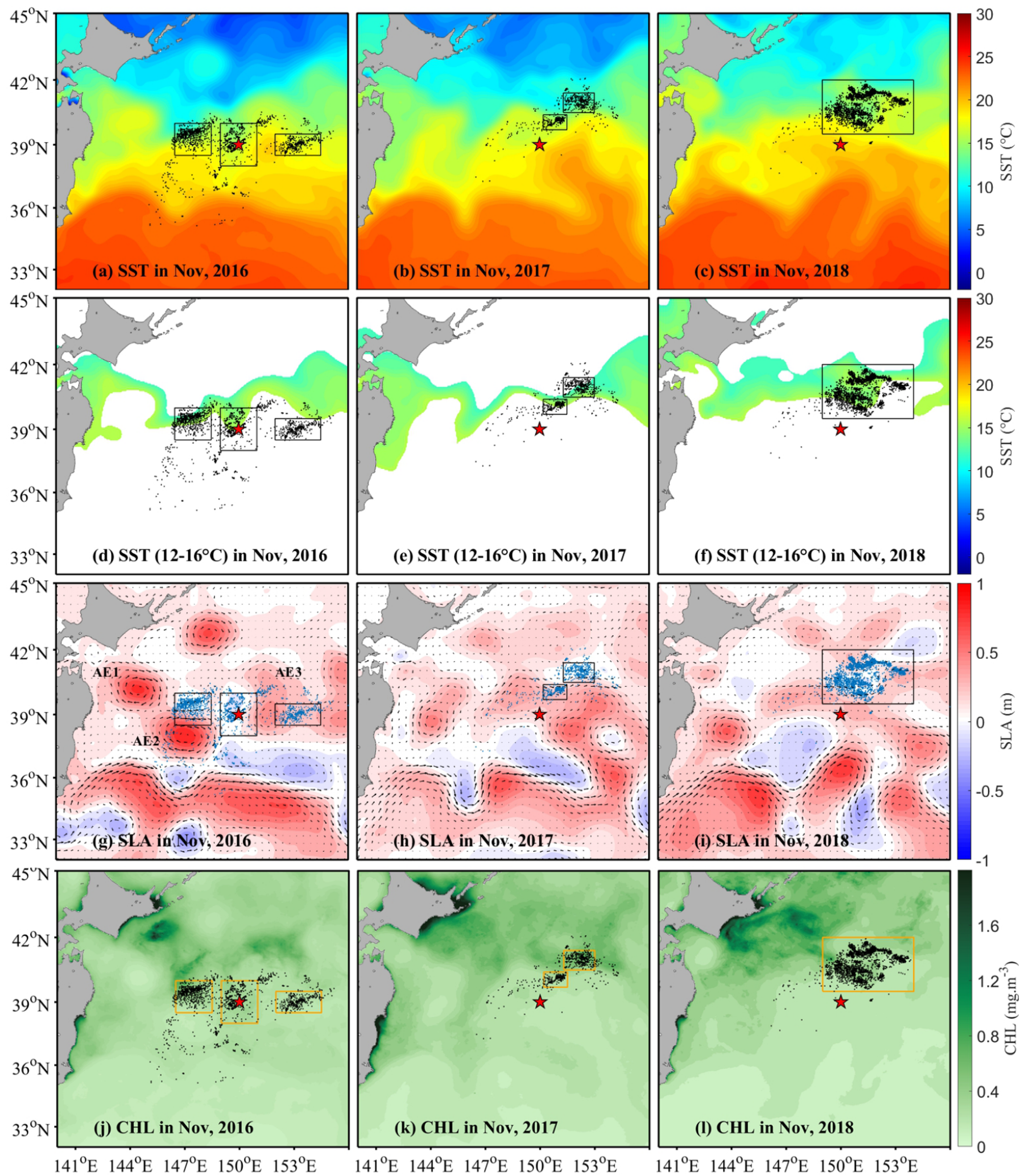


**Fig. 1.** Oceanographic conditions in the Kuroshio–Oyashio Extension (KOE) region during November 2016–2018. (**a–c**) Sea surface temperature. (**d–f**) 12–16°C SST isotherms. (**g–i**) Sea level anomaly superimposed by surface current vectors. (**j–l**) Surface chlorophyll-*a* concentration. Pacific saury fishing vessel locations are denoted by black (a–f, j–l) and blue (g–i) dots, with black (a–i) and yellow (j–l) rectangles highlighting high-density fishing patches. Anticyclonic eddies (AE1, AE2, AE3) identified in November 2016 are labeled in panel (g). Red star represents the location of M2 mooring.

established proxy for zooplankton biomass, supported by a demonstrated linear relationship (Inoue et al. 2016). We used the mean $S_v$ within the 50–150 m depth as our zooplankton abundance indicator guided by sampling depth used in previous Pacific saury feeding habits study (the upper 150 m; Miyamoto et al. 2020), while excluding the noisy 0–50 m layer. The ADCP data featured temporal and vertical resolutions of 1 h and 16 m, respectively, while temperature data was hourly averaged and interpolated onto a 25 m vertical grid. The observational data used in this study spanned October to November 2016. During this period, the M2 mooring captured two anticyclonic eddies and an Oyashio cold tongue event.

Daily satellite data including sea surface temperature (SST; 0.05°), sea level anomaly (SLA; 0.125°), chlorophyll-*a* concentration (CHL; 4 km) and wind velocity (0.125°; 1-hourly interpolated to daily) from October 2016 to November 2018 were collected from the Copernicus Marine Environment Monitoring Service site. Daily finite-size Lyapunov exponent (FSLE) with a 0.04° resolution of November in 2016 was collected from the Archiving, Validation, and Interpretation of Satellite Oceanographic data service site. High FSLE values indicate submesoscale structures, particularly near mesoscale eddy peripheries (Guo et al. 2019; Meunier and LaCasce 2021).

### Synoptic-scale effects on the night-light fishing vessels

The study area was a 2° × 2° area centered on the M2 mooring. To investigate the synoptic-scale wind effects on Pacific saury distribution, we constructed a parameter space using wind speed ($r$) and direction ($\theta$) as polar coordinates. For each fishing vessel location within the target area in November 2016, we projected the corresponding temperature advection induced by Ekman transport and FSLE onto this space. Grid cells were then partitioned into four quadrants (SW, NW, SE, NE) based on $\theta$.

The daily temperature advection induced by Ekman transport (Alexander and Scott 2008; Li et al. 2022) is calculated as follows:

$$\Delta T = -\overline{u}_e \cdot \nabla_h T = -\left(\frac{\tau_y}{\rho_0 f}\frac{\partial T}{\partial x} - \frac{\tau_x}{\rho_0 f}\frac{\partial T}{\partial y}\right) \quad (1)$$

where $\overline{u}_e$ is the surface Ekman transport vector, $\nabla_h$ is the 2D gradient operator, $(\tau_x, \tau_y)$ is the wind stress vector, $f$ is the Coriolis parameter and $\rho_0$ is the reference seawater density.

## Results

### Mesoscale features: Cold tongue and mesoscale eddies contribute to the south shift of Pacific saury fishing ground in November 2016

To assess annual variations in Pacific saury distribution, we analyzed four oceanographic parameters: SST, SLA, CHL, and the 12–16°C SST isotherms—representing the optimal thermal range for the Pacific saury (Syah et al. 2017) (Fig. 1a–f). In November 2016, the fishing grounds shifted southward by over 1° latitude compared to 2017 and 2018, with night-light fishing vessel distributions clustering around the M2 mooring and forming three distinct patches that aligned closely with the 12–16°C isotherm distribution.

This anomalous pattern coincided with enhanced southward transport of cold water along the edge of two anticyclonic eddies AE2 and AE3 in the southern KOE, creating a corridor for cold tongue flocking southward. Notably, surface CHL at fishing locations was consistently moderate ($< 1$ mg m$^{-3}$) across the 3 years (Fig. 1j–l), showing minimal variation and no association with areas of high surface productivity. This discrepancy prompted investigation of subsurface conditions that may better explain Pacific saury habitat selection during cold tongue and anticyclonic eddy interaction events.

The temperature profile revealed the coldest 50–400 m average temperature in November 2016 (Supporting Information Fig. S2), consistent with the southward displacement of 12–16°C SST isotherms (Fig. 1d–f). Current velocity and temperature profile patterns (Fig. 2) delineated three distinct hydrographic regimes: (1) 1–18 October: Initial AE2 northeast edge influence, with subsequent cold tongue advection via the eddy's eastern flank southward flow; (2) 18 October–8 November: Transitional phase featuring convergent flow between AE2 and AE3 peripheries under persistent cold tongue dominance; (3) 8–30 November: Direct AE3 western edge influence combined with cold tongue effects. This progression was associated with continuous zooplankton accumulation, as indicated by increasing 50–150 m $S_v$ values (Fig. 2b). During the same period, the mean surface CHL value within the 2° × 2° study area showed no correspondence with these subsurface $S_v$ trends (Fig. 2b). These findings underscore the necessity of incorporating subsurface biophysical parameters in fisheries habitat models.

### Synoptic-scale westerly winds contribute to congregating night-light fishing vessels

Surface CHL showed a weak correlation with the daily distribution of fishing vessels ($r = -0.05$, $p = 0.79$; Fig. 3a), while the distribution itself varied markedly from day to day. Since mesoscale features typically persist over monthly timescales, this daily variability points to modulation by higher-frequency processes. Synoptic-scale wind forcing emerges as a likely factor, particularly in regions characterized by vigorous mesoscale eddy and frontal activity (Frenger et al. 2013). Although northwesterly winds dominated the background wind field (52.93% occurrence), Pacific saury fishing vessels showed an even stronger preference (69.07% distribution) for these wind conditions (Supporting Information Fig. S3).

According to the M2 mooring data, elevated mean $S_v$ values in the 50–150 m layer were observed during periods of westerly wind influence, particularly under northwesterly wind conditions (Fig. 3b–d, black dashed rectangle). These days coincided with the shoaling of the mesopelagic backscatter maximum layer (Fig. 3c; except 4 November), suggesting wind-driven upward advection of biological materials. A significant positive correlation between zonal wind speed and 50–150 m $S_v$ also existed ($r = 0.4$, $p < 0.05$). Together with lower temperatures and attenuated warming in the 50–150 m layer during northwesterly winds, these patterns suggest that westerly winds enhance the southward transport of cold, productive water and redistribute prey resources vertically and horizontally.

To assess wind-driven impacts on subsurface $S_v$ while minimizing diel vertical migration (DVM) effects, we analyzed

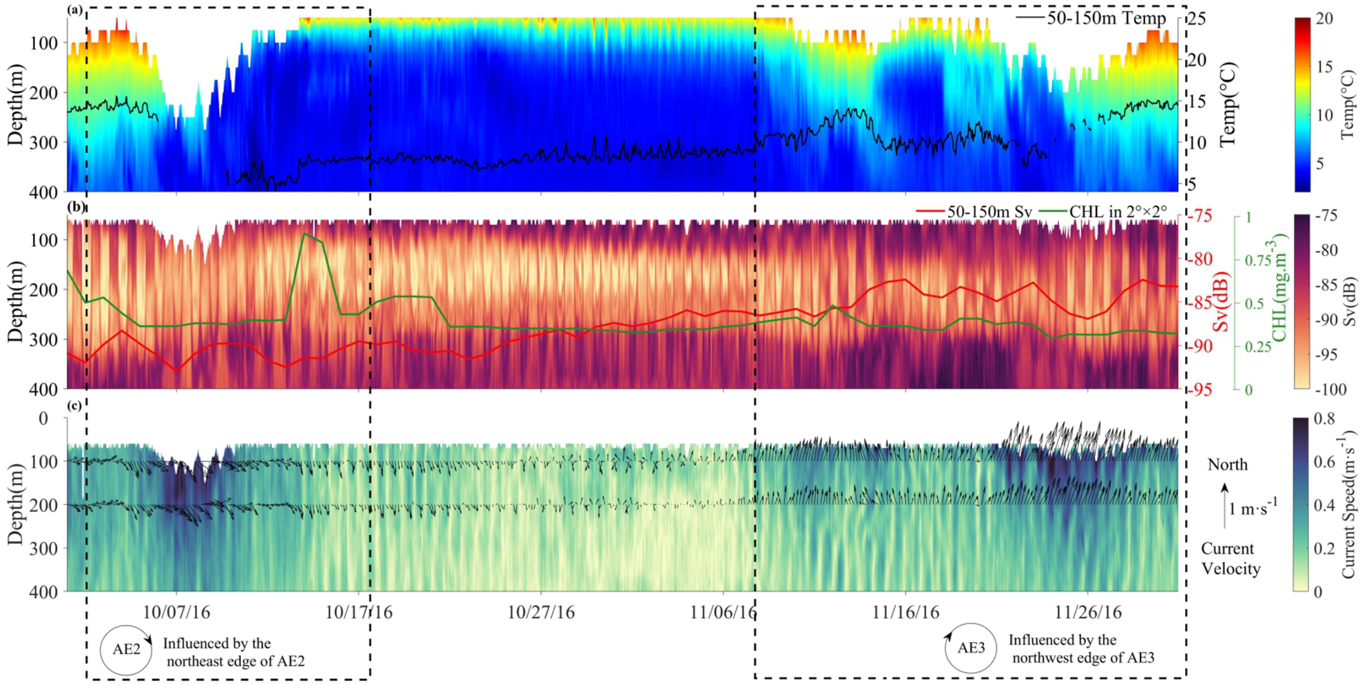


**Fig. 2.** Vertical profiles from M2 mooring observation during October–November 2016. (**a**) Temperature profile and the black solid line indicate the mean temperature of the 50–150 m layer. (**b**) Backscattering strength $S_v$ profile. The red solid line represents mean $S_v$ of 50–150 m and the green solid line represents the mean surface CHL value within the $2^\circ \times 2^\circ$ area centered on the M2 mooring. (**c**) Current speed superimposed by time series of current vectors at 100 m and 200 m depths. Black dashed rectangles highlight periods when the mooring was influenced by the northeast edge of AE2 and northwest edge of AE3, respectively.

50–150 m depth-averaged $S_v$ data synchronized with hourly wind velocity data in November 2016. The 720 $S_v$ measurements (360 daytime/nighttime each) were converted to anomalies ($S_{va}$) and grouped by wind direction (SW, NW, SE, NE). The results revealed that while wind effects were statistically non-significant ($p = 0.54$; Fig. 3e) during daytime, northwesterly winds still corresponded to the highest median $S_{va}$. At night, the influence of westerly winds became statistically significant ($p < 0.01$; Fig. 3f). This pattern remained significant ($p < 0.05$; Supporting Information Fig. S4) when integrating data across the full diel cycle, confirming that westerly winds promote the increase in subsurface $S_v$.

We further investigated synoptic-wind influences on Pacific saury fishing grounds by analyzing daily temperature advection induced by Ekman transport ($\Delta T$) and finite-size Lyapunov exponent (FSLE) at the fishing locations (Fig. 4). Most data points were distributed within the NW quadrant. While the median FSLE value existed in all four quadrants, almost all high FSLE values clustered in the NW and SW quadrants (Fig. 4b), and positive FSLE anomalies emerged only under the effect of NW and SW winds (Fig. 4c). Selecting night-light fishing vessel locations within the $2^\circ \times 2^\circ$ region during November 2016 and applying the threshold FSLE > mean + $\sigma$ (Guo et al. 2019; where $\sigma$ is the standard deviation) to identify submesoscale activity, we found that FSLE anomalies under westerly winds were significantly higher than under easterly winds (Fig. 4d; $p < 0.01$). Concurrently, nearly all the data points in the NW and SW quadrants showed negative $\Delta T$ values (Fig. 4a), with negative anomalies under westerly winds (Fig. 4c). These results indicate that westerly winds drive cold water transport and submesoscale nutrient injection, creating biophysical conditions that favor Pacific saury aggregation in southern areas.

## Discussion

Marine fishes exhibit distinct habitat preferences governed by physiological optima across biotic and abiotic factors (Braun et al. 2019; Bouchet et al. 2017; White et al. 2019; Houde 2008), with Pacific saury being no exception. These preferences are modulated by multi-scale oceanic processes, particularly mesoscale eddies and frontal systems that dominate the KOE region (Storch et al. 2012; Ueno et al. 2023; Jing et al. 2019). While such features typically regulate marine productivity and fish habitat formation (Yatsu et al. 2013) through sharp thermohaline gradients (D'Asaro et al. 2011; Xing et al. 2024a), their impacts on Pacific saury can be spatially variable: anticyclonic eddies southeast of Hokkaido inhibit coastal fishing ground formation by blocking Oyashio transport (Kuroda and Yokouchi 2017), whereas our findings

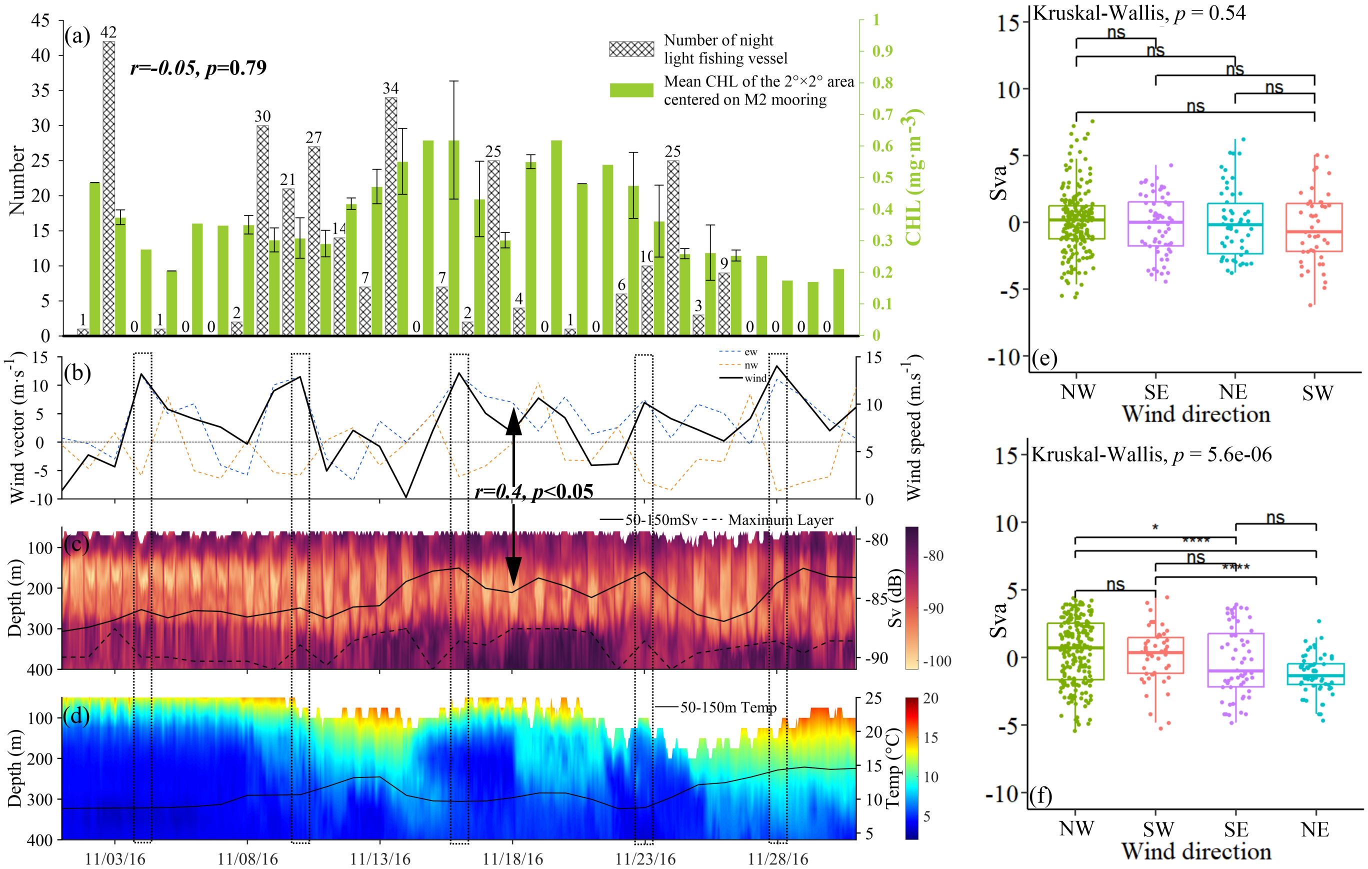


**Fig. 3.** (**a**) Daily distribution of night-light fishing vessels (gray bars; vessel counts shown above bars) and mean CHL value of the 2° × 2° area (green bars; error bars above calculated from CHL values at the location of every night-light fishing vessel on the corresponding day). (**b**) Wind condition at M2 mooring: wind speed (black solid line) and vector components (eastward: blue dashed line; northward: orange dashed line). (**c**) Depth-time profile of backscattering strength $S_v$ with depth-averaged values for 50–150 m (black solid line) and the depth of maximum layer (black dashed line). (**d**) Temperature profile with 50–150 m mean temperature (black solid line). (**e** and **f**) Distribution of $S_v$ anomalies ($S_{va}$) by wind direction during daytime and nighttime, respectively.

reveal offshore anticyclonic eddies can contribute to the high-sea habitat formation through the following potential mechanisms: (1) the southward transport of nutrient-rich cold water along eddy edges. (2) the vertical nutrients mixing existing in the edge of anticyclonic eddy (Qu et al. 2022). (3) enhanced vertical exchange promoted by interactions between two anticyclonic eddies (Dai et al. 2023).

In November 2016, synoptic-scale winds interacted with these mesoscale features and contributed to the formation and influenced the distribution of biologically active zones suitable for Pacific saury through the following mechanisms: (1) The southward Ekman transport (Griffin and Middleton 1992; Middleton et al. 1996) induced by westerly winds enhanced the cold tongue–anticyclonic eddy intersection, generating a superimposed effect that facilitates vertical mixing and nutrient upwelling and brought the cold Oyashio water to the south. (2) Wind–eddy current differentials can generate vertical motions through Ekman pumping (Dewar and Flierl 1987; McGillicuddy et al. 2007), increasing nutrient mixing and prey availability. (3) Submesoscale processes are active at the edge of mesoscale eddies (Siegel et al. 2011), where many strong fronts are also present. D'Asaro et al. (2011) demonstrated that along-front winds interacting with frontal structures can initiate an energy cascade that enhances turbulent mixing and sustains submesoscale motions, characterized by strong vertical motions (Klein and Lapeyre 2009; Martin and Richards 2001; Sasaki et al. 2014). In our study, westerly winds may amplify such submesoscale activity along eddy edges, thereby contributing to the enhancement of subsurface productivity.

This multi-scale interaction created ephemeral biological hotspots where Pacific saury aggregated, demonstrating that synoptic-scale winds can override mesoscale habitat baselines. For the pelagic fishing industry, accurate short-term forecasts are crucial for enabling fleets to devise more efficient fishing strategies and enhance operational profitability. Therefore, integrating synoptic-scale features and their impacts on mesoscale oceanic processes into forecast models is essential. Future

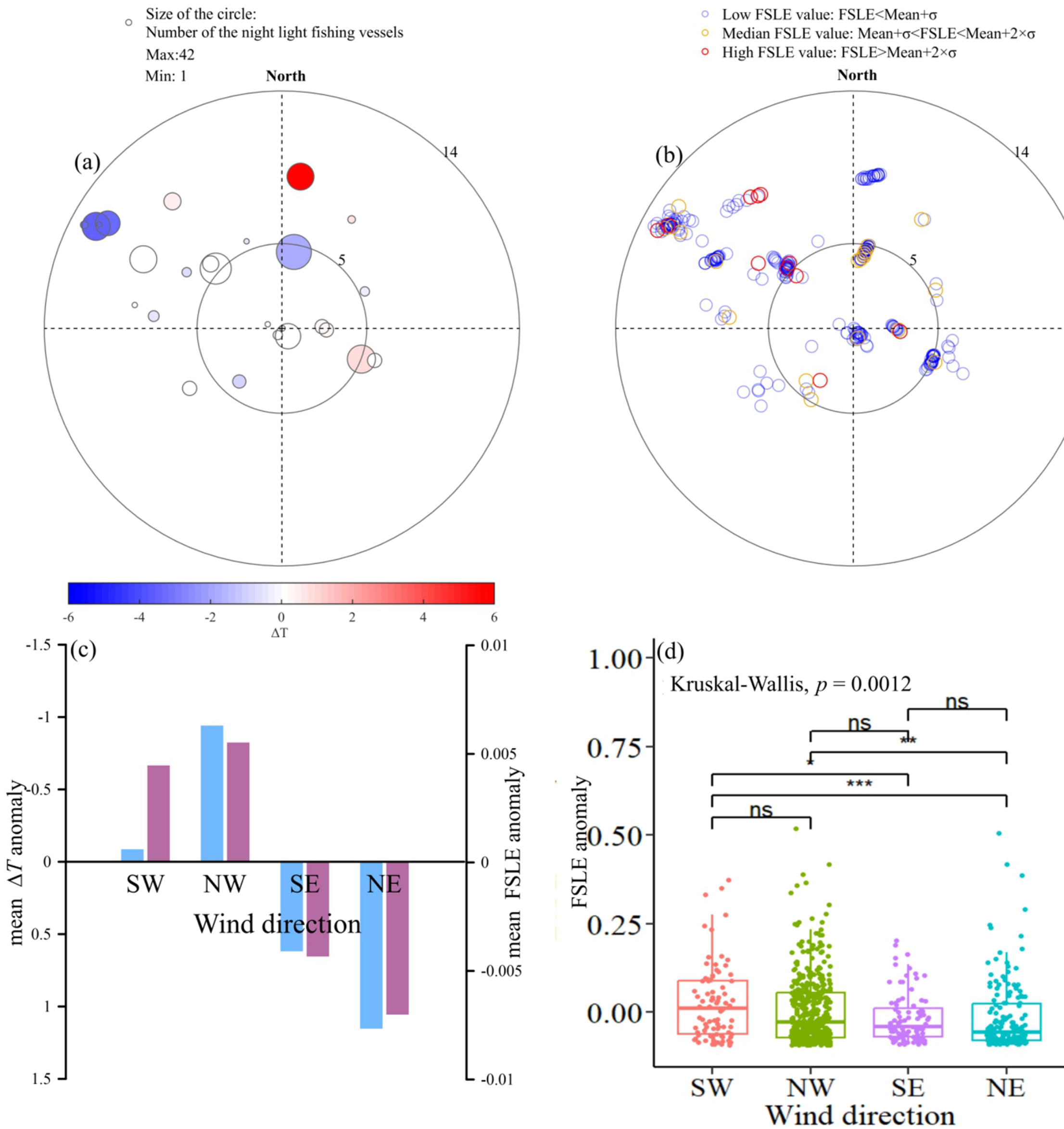


**Fig. 4.** Wind-driven oceanographic processes affecting Pacific saury night-light fishing vessels in November 2016. (**a**) Polar plot of averaged daily Ekman-induced temperature advection vs. wind speed ($r$) and direction ($\theta$), with dot size proportional to fishing vessel number and color indicating $\Delta T$ magnitude. (**b**) Corresponding FSLE values classified by intensity (high: red; medium: yellow; low: blue). (**c**) Wind-directional response of $\Delta T$ and FSLE anomalies. (**d**) Distribution of FSLE anomalies by wind direction.

models should explicitly incorporate key atmospheric forcing variables, such as wind speed and direction, as direct inputs to quantify wind-induced mixing and advection, thereby improving predictions of short-term fishing ground formation.

While large-scale seas surface remote sensing data (e.g., SST, SSH, CHL) are widely used in fishery studies due to their accessibility, these surface proxies exhibit fundamental limitations in elucidating the three-dimensional mechanisms of Pacific saury fishing ground formation: (1) CHL spans multiple trophic levels and may not reflect saury feeding conditions (Liu et al. 2022). (2) Pacific saury's vertical habitat range: 0-230 m (Tseng et al. 2011) necessitates euphotic-zone integrated assessment rather than surface-only observation. (3) Oceanic stratification often decouples subsurface features from surface signatures (Crawford et al. 2007; He et al. 2023). Subsurface mooring systems overcome these constraints by providing continuous depth-resolved measurements of both physical parameters and zooplankton distributions through ADCP r acoustic devices, enabling direct quantification of prey dynamics at ecologically relevant depths. This is critical for understanding fish aggregation patterns, as zooplankton vertical distribution metrics directly reflect the biophysical forcing mechanisms structuring fishable populations.

This study provides direct evidence, through continuous subsurface observations at the M2 mooring, that the anomalous southward migration of the Pacific saury in November 2016 was driven by the combined effects of mesoscale ocean features (the Oyashio cold tongue, anticyclonic eddies) and synoptic-scale winds (Fig. 5). We demonstrate that these multi-scale processes improved subsurface feeding conditions, which ultimately reshaped the Pacific saury fishing ground distribution.

This is the first application of high-resolution mooring data to assess environmental variability in high sea fishing grounds, revealing its unique advantage in resolving subsurface ecological dynamics and fine-scale habitat features. However, one constraint of this study is its reliance on data from one single mooring data to deduce fishing ground formation mechanisms, assuming similar marine environmental conditions within the same ocean process control zone. Given the extensive spatial influence of mesoscale ocean processes in the open ocean, this assumption is reasonably valid. However, the deployment of mooring networks will undoubtedly yield more accurate results.

Another constraint of this study lies in the use of fishery-derived data, which reflects commercial fishing operations rather than a systematic scientific assessment. However, fishery-derived data, especially from night-light remote sensing, offer a decent alternative data when there is a lack of scientific survey, considering its high spatiotemporal resolution and good accessibility. Therefore, fishery-derived data like night-light fishing vessel data has been extensively and successfully employed in previous fishery researches (Liu et al. 2015; Waluda et al. 2002, 2004; Tian et al. 2022). In addition, the high spatiotemporal resolution of the night-light fishery data also meets the requirement of studying high-frequency fishing grounds variations.

Our findings describe a specific scenario in which westerly winds enhance zooplankton aggregation, thereby affecting Pacific saury distribution. This biophysical coupling is not universally applicable across all marine regions. Its validity is scenario-dependent and the specific pattern would change with the shift of relative positions of warm and cold water masses. Nevertheless, the wind-driven processes identified in this study extend beyond isolated events and represent a manifestation of a globally relevant mechanism. On a global scale, winds interact with oceanic fronts to enhance turbulence and nutrient supply to the euphotic zone through mechanisms such as wind-driven mixed-layer deepening, Ekman buoyancy flux, and symmetric instability (Whitt et al. 2017a; Whitt et al. 2017b; Mole et al. 2025; Koenig et al. 2020). This wind-front interaction can be particularly pronounced in major frontal systems between subtropical and subarctic water (with

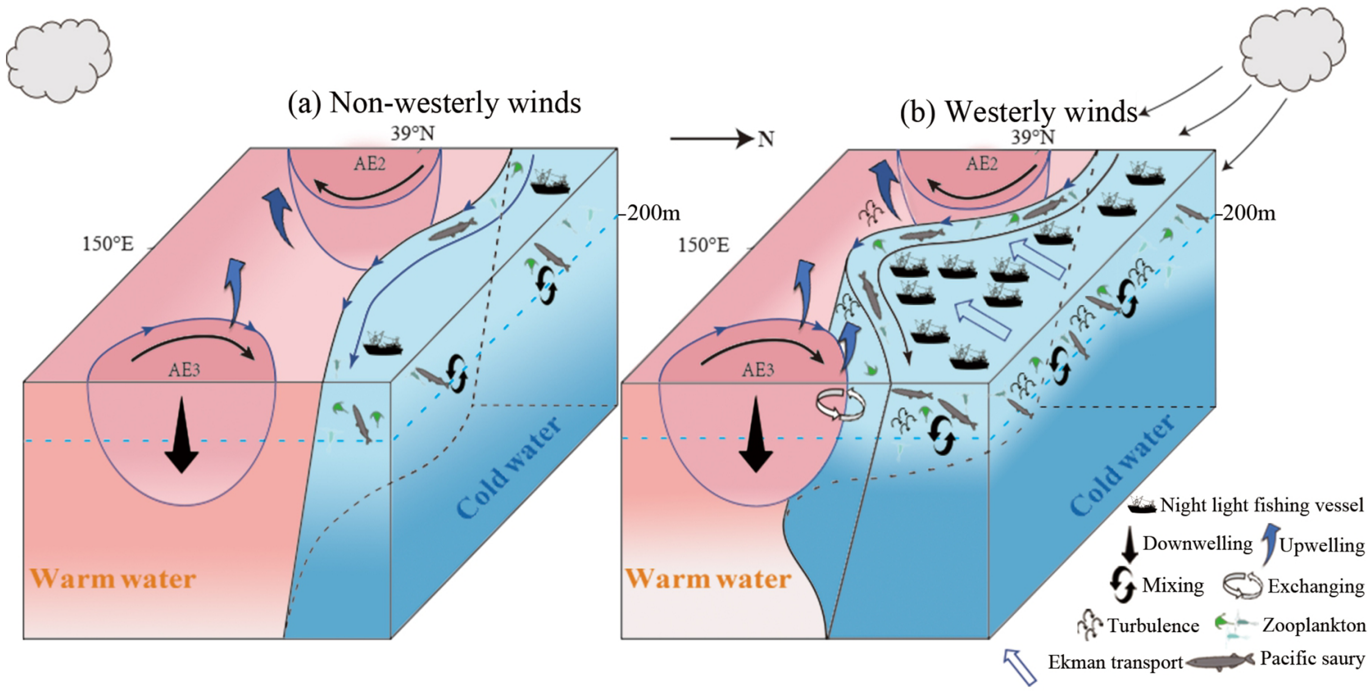


**Fig. 5.** Schematic illustrating wind-mediated habitat enhancement for Pacific saury in November 2016. (**a**) Baseline condition under non-westerly winds shows limited interactions between the Oyashio cold tongue and anticyclonic eddies. (**b**) Synoptic-scale westerly winds can promote vertical mixing and the upper layer feeding environment through inducing southward Ekman transport and intensifying eddy–cold tongue interactions, thereby improving the aggregation of Pacific saury within a relatively short spatiotemporal scale.

possibly various wind direction driving processes in different regions), significantly stimulating plankton growth and regulating ocean carbon sequestration, underscoring their role as fundamental drivers of global marine biogeochemical cycles (D'Asaro et al. 2011). Our mooring-based observations further reveal that wind forcing can also indirectly influence the distribution of higher-trophic-level organisms, such as Pacific saury. To scale the point findings to regional fishing ground three-dimensional dynamics and build a predictive framework linking wind forcing to fisheries productivity, it is essential to establish more fixed-point continuous observation stations. Such an integrated observing system will be critical for elucidating the full ecological pathway: from wind forcing to nutrient enrichment, phytoplankton blooms, and zooplankton aggregation, thereby supporting the sustainable management of pelagic fisheries.

## Author Contributions

Jianchao Li, Zhaohui Chen, and Yongjun Tian conceived the study. Yulei Zhang, Ruichen Zhu, and Hao Tian analyzed data. Yulei Zhang and Jianchao Li wrote the manuscript draft. Yang Liu, Peng Sun, Zhenjiang Ye, and Yongjun Tian contributed to the revision of the manuscript. All authors approved the final version of the manuscript.

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## Conflicts of Interest

None declared.

### Data Availability Statement

The datasets generated and analyzed during this study are available at https://doi.org/10.5281/zenodo.17785798. Sea surface temperature (SST), sea level anomaly (SLA), chlorophyll-*a* concentration (CHL), and wind data were obtained from the Copernicus Marine Environment Monitoring Service (CMEMS) using the following products, respectively: https://doi.org/10.48670/moi-00169, https://doi.org/10.48670/moi-00148, https://doi.org/10.48670/moi-00281, and https://doi.org/10.48670/moi-00185. Finite-size Lyapunov exponent (FSLE) data were provided by the Archiving, Validation and Interpretation of Satellite Oceanographic Data (AVISO) service at https://doi.org/10.24400/527896/a01-2022.002.

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## Supporting Information

Additional Supporting Information may be found in the online version of this article.

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