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Article

Effects of Kuroshio and Mesoscale Eddy on Fishing Ground Gravity of Neon Flying Squid *Ommastrephes bartramii* in Northwest Pacific Ocean

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Abstract: Understanding the spatial patterns of neon flying squid is important for the monitoring and management of fishery resources. Mesoscale eddies and the Kuroshio Extension play important roles in the variation of the fishing ground of *Ommastrephes bartramii*. However, the way in which eddies and the Kuroshio influence the distribution of *Ommastrephes bartramii* requires further understanding. In this study, the spatial variation in the distribution of fishing activity and the change of fishing ground gravity of squid were analyzed using automatic identification system (AIS) data. There is a positive correlation between the fishing ground gravity in latitudinal direction and Kuroshio Extension indicators based on the high-frequency eddy kinetic energy (EKE), which describes the Kuroshio variations. Furthermore, the Kuroshio Extension indicators show a positive relationship with the number of the eddies generated in the fishing ground. The results suggest that the changes in the dynamics of SST anomalies could be influenced by eddy-shedding processes in the upstream KE and then alter the distribution of the fishing ground for *Ommastrephes bartramii*. The Kuroshio index (mean high-frequency eddy kinetic energy between 32° and 37° N, 142° and 149° E) can be used as a good indicator of Kuroshio extension variations to investigate the squid fishing ground in the Kuroshio–Oyashio transition area.

Keywords: squid-jigging vessels; fishing effort; marine environmental; Kuroshio; mesoscale eddy

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1. Introduction

The red flying squid (*Ommastrephes bartramii*) is an extremely widespread ommastrephid species, inhabiting subtropical and temperate waters within a year's life [1]. In the temperate and partly tropical regions, *Ommastrephes bartramii* prefer to inhabit warm waters and cold boundary currents, respectively. Sea surface temperature plays an important role in the distribution of *Ommastrephes bartramii*, which occurs in areas with sea surface temperatures between 10 °C and 25 °C [1–3].

The North Pacific population of red flying squid is represented by an autumn cohort that spawns in the area between 20 and 30° N and 130 and 170° E from September to February, and a winter-spring cohort that spawns from January and May [4]. The western stock of the winter–spring cohort migrates to the main feeding grounds between 38 and 46° N, 150 and 165° E during the summer and is the main target of Chinese jigging vessels [5]. From July to November, the Chinese squid jigging in the North Pacific is mainly distributed between 150° and 165° E and 40° and 46° N, and the fishing area has expanded eastwards to 170° W [5,6]. The annual catch of the North Pacific squid fishery during the period 2009–2019 has ranged from 15,900 to 66,000 tones, with an average annual catch of 42,200 tones [7].

The neon flying squid in the North Pacific migrate to the feeding grounds in subarctic waters and return to the spawning grounds in subtropical waters [8,9]. The distribution of squid fishing grounds is influenced by several marine environmental factors, in particular, the sea surface temperature (SST), sea surface salinity (SSS), and sea surface height (SSH) are considered to be the most influential environmental factors affecting the distribution of the potential squid fishing grounds [3,10–14]. In addition, chlorophyll-a (Chl-a) concentration, climate change, eddy kinetic energy (EKE), and wind stress curl also affect potential fishing grounds for squid [4,10,15].

According to previous studies based on fishing effort (FE) information calculated from automatic identification system data of squid jigging vessels, the squid jig fishery was mainly distributed at 41–44° N, 152–165° E, with the favorable ranges of SST, SSH, SSS, and Chl-a between 15–18 °C, 0–0.2 m, 0.2–0.4 mg m^{-3}, respectively [11].

Squid fishing ground is strongly affected by the Kuroshio–Oyashio transition zone, which is a mixture of the warm and saline waters associated with the Kuroshio Current (KC), and the cold and less-saline waters which are dominated by the Oyashio Current (OC). There is an abundance of mesoscale eddy activity in the Kuroshio–Oyashio transition zone, which can affect the primary productivity [16] and fisheries by modulating the physical properties of seawater and the nutrient fluxes in both the horizontal and vertical directions [17–19].

The squid fishing ground is closely related to the Kuroshio front and Oyashio fronts [12,20–22]. The squid habitat off the east coast of Japan was highly relevant to the edge of a warm core ring south of the Oyashio water. That is, the mixing process of the warm and nutrient-poor Kuroshio water with the cold and nutrient-rich Oyashio water created a favorable environment for the feeding grounds of the neon flying squid [12]. In addition, the catches of the squid jigging fishery were also influenced by the Kuroshio, for example, the results of Shao et al. [23] showed that the catch per unit effort increased when the Kuroshio showed small bends or quasi-bends, but decreased when the Kuroshio path was straight or showed large bends [23].

Chen et al. [24] suggested that the path dynamics of the Kuroshio at 136–140° E influenced the fluctuations of the SST anomaly at 40–43° N, 150–155° E, and further led to the northward or southward shift of the thermally favorable areas for *Ommastrephes bartramii*. Zhang et al. [6] suggested that the eddy activities attracted *Ommastrephes bartramii* by modulating the thermal conditions, for example, the unstable KE system facilitated the suitable thermal conditions combined with favorable foraging conditions and may contribute to the high yield of squid jigging fishery in warm eddies. However, there are some difficulties in studying the Kuroshio path meander due to a lack of data, and further studies are needed to understand how the path of upstream KE affects heat transport [24].

The aim of the present study is to investigate the Kuroshio Extension system and associated eddy activity on the variation of squid-jigging fishing grounds. Based on the fishing effort of the jigging fishery, mesoscale eddies and the marine environmental factors, the gravity of the fishing effort for squid jigging is calculated and the relationship between the distribution of monthly fishing effort and environmental variables is analyzed. Finally, the effects of mesoscale eddies and Kuroshio on the shifting of the gravity of the squid fishing ground are discussed.

2. Materials and Methods

2.1. Study Area

The study area covers the traditional fishing grounds of neon flying squid (*Ommastrephes bartramii*) between 145° E and 170° E and 35° N and 50° N in the western North Pacific, which are influenced by the Kuroshio and the Oyashio Currents [25].

The Kuroshio currents flow off the east coast of Japan (35° N, 140° E) and form the Kuroshio Extension (KE), which is characterized by an eastward-flowing jet with large-amplitude meanders and energetic eddies [26–28]. The variability of Kuroshio Extension exhibits two distinct states: a 'weak state' (also called 'contracted state') in which the KE jet velocity is weaker and more unsteady, spreading over a wider latitudinal band, and an 'elongated state' corresponding to a narrow, strong steady jet [29]. The KE system is associated with the strongest mesoscale eddy activity [30]. The mesoscale eddies separated from the KE have important influences on the water properties such as temperature, salinity and chlorophyll-a in both the horizontal and vertical directions [16].

2.2. Fishing Effort of the Jigging Fishery

Fishing effort for the jigging fishery in 2012–2020 was obtained from the Global Fishing Watch AIS-based fishing effort and vessel presence datasets (http://www.globalfishingwatch.org, accessed on 1 June 2022). The data recorded the fishing effort by flag state and gear type at a resolution of 0.01-degree for 2012–2020. The fishing effort was measured in units of hours for 2012–2020 [31].

The gravity center of squid ground during August, September and October in 1998–2007 was obtained by FAN, et al. [32]. The gravity center of squid ground was derived from logbook information for Chinese squid-jigging vessels (including fishing date, fishing locations of squid-jigging between 39–46° N, 150–165° E, and catch) that were collected by the Chinese Squid-Jigging Science and Technology Group of Shanghai Ocean University.

2.3. Environmental Data

The environmental variables used in this study include sea surface temperature (SST), sea surface salinity (SSS), sea level anomalies (SLA), eddy kinetic energy (EKE), and chlorophyll-a (Chl-a) during the period 2012–2020. The monthly SST and Chl-a with a spatial resolution of 1/6 degree were downloaded from the Oregon State University's Ocean Productivity database (http://sites.science.oregonstate.edu/ocean.productivity/, accessed on 1 June 2022). The SSS was obtained from IAP global ocean temperature gridded product with a horizontal resolution of 0.5° × 0.5° provided by the Marine Science Data Center, Chinese Academy of Sciences [33]. The monthly mean SLA and EKE data with 0.25-degree spatial resolution were obtained from Ssalto/Duacs multimission altimeter products that were processed by SSALTO/DUACS and distributed by AVISO+ (https://www.aviso.altimetry.fr, accessed on 1 June 2022) with support from CNES. The environmental variables at different spatial resolutions were resampled to a spatial resolution of 1 degree and a monthly temporal resolution, the same as the fishing effort of the squid-jigging fishery.

Sea surface temperatures anomaly (SSTA) values in the Niño 3.4 region (Oceanic Niño Index) were obtained from the NOAA Climate Prediction Center (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php, accessed on 1 June 2022). A minimum of five consecutive 3-month running mean of SSTA in the Niño 3.4 region surpassing the threshold of +0.5 °C (−0.5 °C) indicate the warm (cold) phases, also known as El Niño (La Niña) episodes.

2.4. Mesoscale Eddy

The mesoscale eddy trajectories atlas (META3.2) was produced by SSALTO/DUACS and distributed by AVISO+ (https://aviso.altimetry.fr, accessed on 1 June 2022) with support from CNES in collaboration with Oregon State University with support from NASA. The eddies in META3.2 were detected from the multimission altimetry dataset with the observation time, coordinates, eddy radius, eddy amplitude, eddy rotation speed, and rotation type (cyclonic/anticyclonic) [34–36]. In this study, the eddies generated between 35° and 50° N as well as 145–170° E, which is the distribution area of the jigging fishery for neon squid in the North Pacific, were selected.

2.5. Eddy Kinetic Energy

The Kuroshio Extension index, an average of the high-frequency eddy kinetic energy over a box located between 142 and 149° E and 32 and 37° N, was obtained from AVISO+ (https://data.aviso.altimetry.fr/aviso-gateway/data/indicators/kuroshio/, accessed on 1 June 2022) [37]. The Kuroshio Extension index greater than 0.2 indicates a contracted state of the unsteady KE, while the Kuroshio Extension index less than −0.2 indicates an elongated state of the strong steady KE. Between the contracted state and the elongated state, the KE has many neutral transition states and shows either progressive weakening or strengthening trends.

2.6. Gravity of Fishing Effort

The gravity of fishing effort for squid jigging from July to September was calculated for the period 2012–2020. The gravity of fishing effort was calculated as follows:

$$G_x = \frac{\sum_{i=1}^{n}(E_i \times Lon_i)}{\sum_{i=1}^{n} E_i}, G_y = \frac{\sum_{i=1}^{n}(E_i \times Lat_i)}{\sum_{i=1}^{n} E_i} \quad (1)$$

in which G_x and G_y are the longitudinal gravity center of fishing effort and the latitudinal gravity center of fishing effort. E_i is the fishing effort for squid jigging in the i-th grid area. Lon_i and Lat_i are the longitudinal mid-point of the i-th grid area and the latitudinal mid-point of the i-th grid area, respectively.

2.7. Pearson Correlation Coefficient

The Pearson correlation coefficient r represents the strength of a linear association between the two factors X and Y. The value r can range from −1 to 1, where the value r = 1 means a perfect positive correlation between X and Y, r = −1 means a perfect negative correlation between X and Y, and r = 0 value indicates that no relationship exists between the variables X and Y. Before calculating a Pearson correlation, the Shapiro-Wilk test of normality was used to assess whether the data set was approximately distributed along a normal distribution curve. The result of Shapiro–Wilk normality test for Kuroshio indicators, latitudinal gravity centers of fishing ground and eddies Number are shown in Table S1 in the Supplementary Materials.

The Pearson Correlation Coefficient r can be calculated as follows:

$$r = \frac{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)}{\sqrt{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2}\sqrt{\sum_{i=1}^{n}\left(Y_i - \overline{Y}\right)^2}} \quad (2)$$

in which n is sample size, X_i and Y_i are the individual data points indexed with i, and $\overline{X}$ and $\overline{Y}$ are the mean values of the factors X and Y, respectively.

3. Results

3.1. Distribution of Monthly Fishing Effort and Environment Factors

As shown in Figure 1, there is a clear trend of an increase in fishing effort on squid jiggers from July to September and then a gradual decrease in October and November. The fishing effort remained at a relatively high level from August to October, reflecting the main fishing season for squid fisheries in the North Pacific. A minimum value of squid jigger fishing effort occurs in July (Figure 1). The high values of fishing effort from August to October clearly reflect the fishing season when the SST in the fishing ground increased to a high level (Figure 1). In general, the mean values of SST in the squid fishing grounds were relatively lower in July and November, while the mean SST rose to higher values in August, September and October, except in 2012–2013.

The mean monthly Chl-a ranged from 0.20 mg m^{-3} to 0.64 mg m^{-3}. The Chl-a concentration generally increased from July to October and decreased in November (Figure 1). The mean monthly SLA in fishing grounds ranged between 0.09 m and 0.24 m. Changes in mean monthly SLA showed a similar trend with Chl-a (Figure 1). The values of mean monthly EKE in the fishing ground were relatively stable in July, August and September. However, the EKE showed a significant increase in October and November (Figure 1).

The values of the monthly mean SSS fluctuated within a narrow range of 33 to 34 g kg^{-1} throughout the study period (Figure 1).

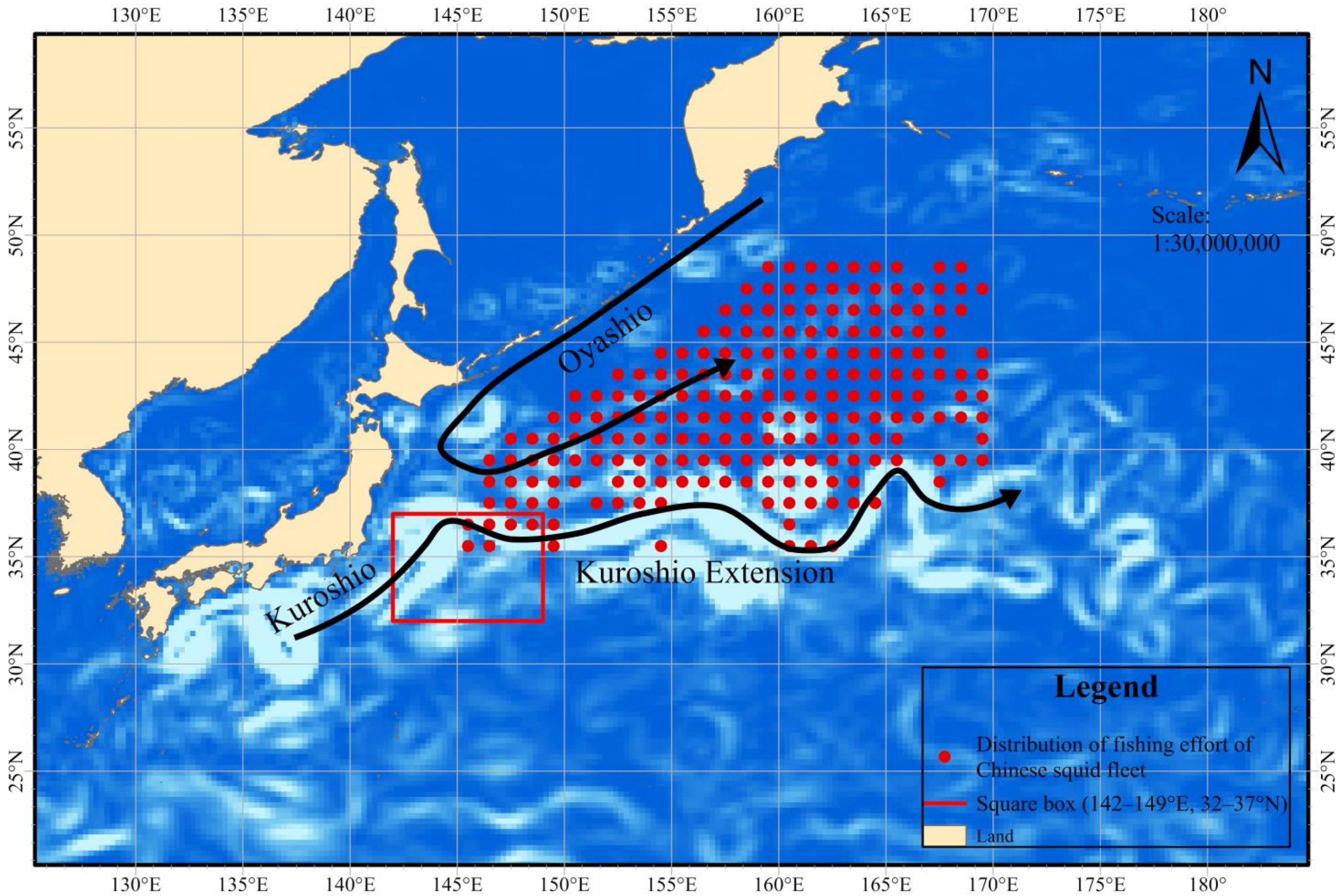

Figure 1. The schematic diagram of distribution of the fishing effort for squid-jigging vessels in the Northwest Pacific during 2012–2019 (red dots). The red square box, in which mean high-frequency EKE was defined as a Kuroshio Extension indicator that correspond to elongated/contracted states of the Kuroshio Extension, is located between 142 and 149° E and 32 and 37° N.

3.2. Fishing Effort and Environmental Factors

The distribution of fishing effort (hours) follows normal distributions with SST, Chl-a, SLA and SSS in the squid fishing ground (Figure 2), except for the EKE which follows a lognormal distribution (Figure 2).

Fishing effort for neon flying squid was distributed in sea areas with values of SST between 7–27 °C, Chl-a between 0.05–1.7 mg m^{-3}, SLA between −0.15 m and 0.94 m, and SSS between 32.57–34.63 g kg^{-1}, respectively (Figure 2). The cumulative percentage of the fishing effort located in areas with EKE between 3.6 and 400 cm^{2}s^{-2} is 91.12%, increasing to 99.07% in the areas with EKE between 3.6 and 1100 cm^{2}s^{-2}.

The squid jigging fishery is concentrated in the following areas: SST ranging between 10 and 23 °C, Chl-a ranging between 0.1 and 0.7 mg m^{-3}, SLA ranging between 0 and 0.4 m, and SSS ranging between 32.6 and 34.5 g kg^{-1}.

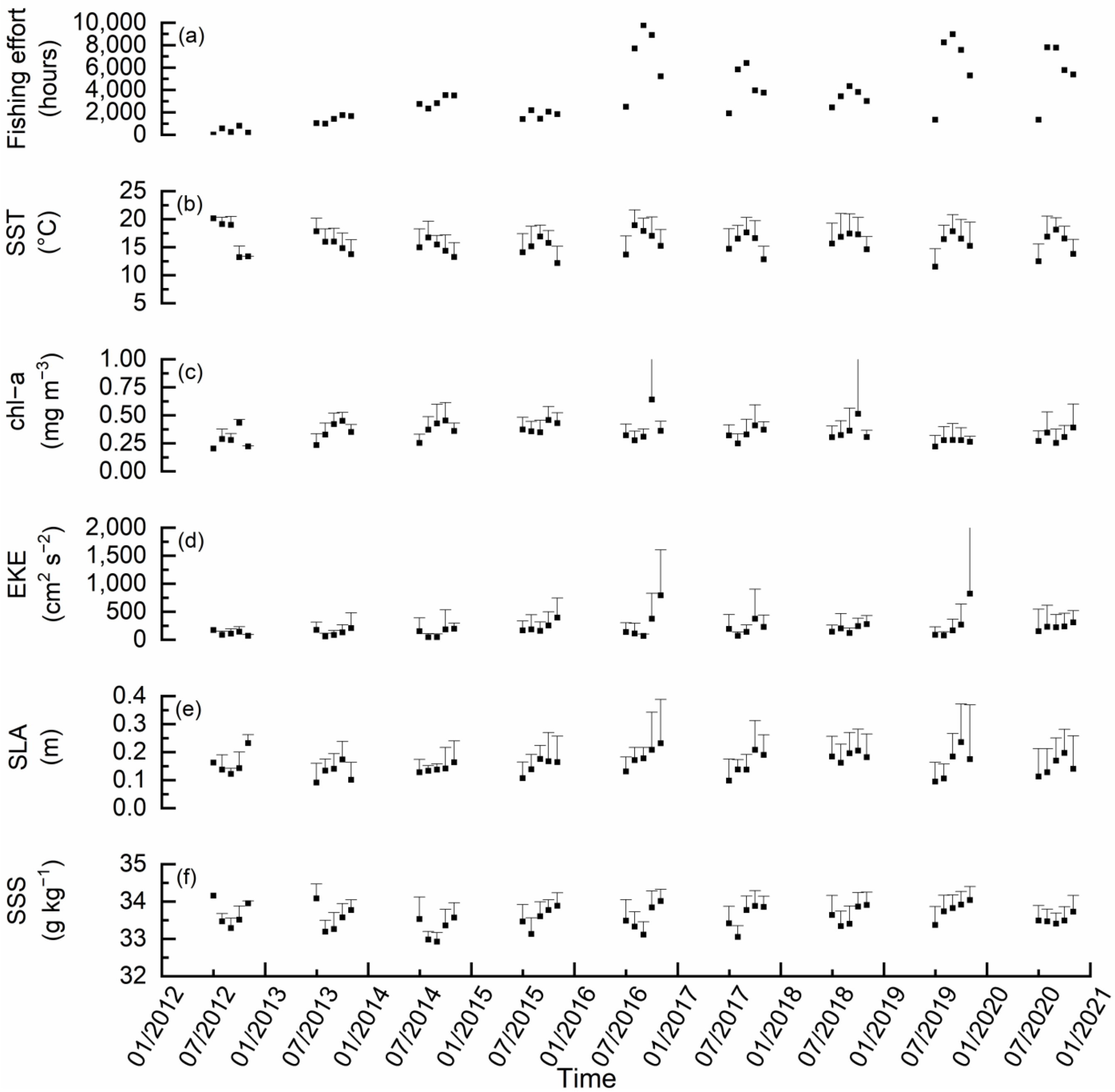

Figure 2. (**a**) Monthly fishing effort for squid-jigging (hour) from July to November, and monthly mean (**b**) sea surface temperature (SST, °C), (**c**) chlorophyll-a (Chl-a, mg m^{-3}), (**d**) eddy kinetic energy (EKE, cm^{2}s^{-2}), (**e**) sea level anomalies (SLA, m), (**f**) sea surface salinity (SSS, g kg^{-1}) of the squid ground in the western North Pacific (145–180° E, 35–50° N) during 2012−2020.

3.3. Variations in the Distribution Centroid of the Squid Fishing Ground

In this study, the fishing effort for squid jigger was mainly distributed in the area between 36–48° N and 146–170° E. The gravity centers of fishing effort for squid jigger were located in 40.98–44.41° N, 151.79–163.14° E from August to October in the periods 1998–2007 and 2012–2020 (Figure 3). The changes in the latitudinal gravity centers of fishing ground for squid jigger followed a similar trend to the changes in the mean Kuroshio indicators between August and October. As the Kuroshio indicators decreased in 2001–2003 and 2014–2018, the latitudinal gravity centers decreased, indicating that the gravity of jigging activities shifted southwards (Figure 3). On the contrary, as the Kuroshio indicators increased in the period 2003–2005, the latitudinal centroids also increased. The mean

Kuroshio indicators between August and October remained high in the periods 1999–2001 and 2012–2014. At the same time, the latitudinal centers of gravity increased, showing that the squid jigging fleets were moving further north.

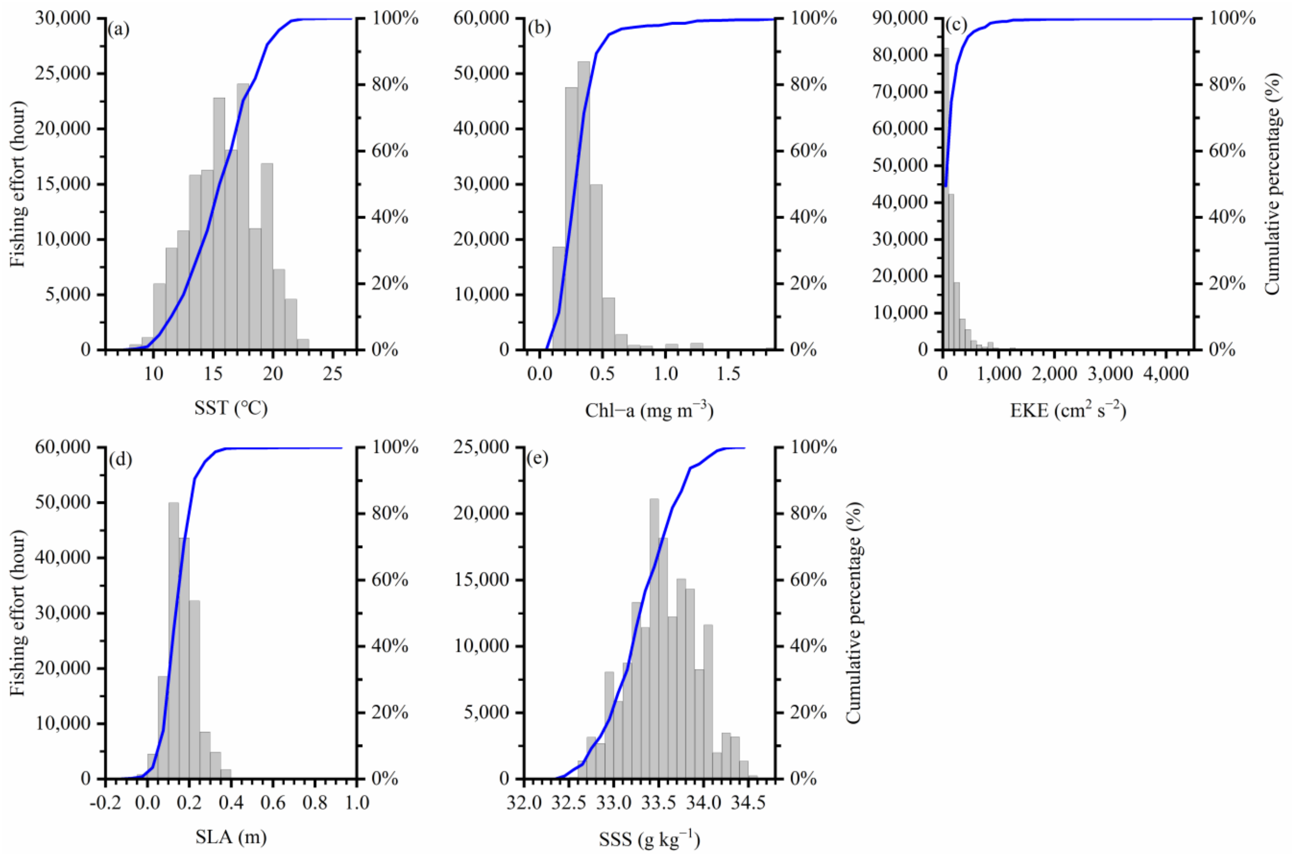

Figure 3. Fishing effort (hour) distribution (left vertical axis) and cumulative percentage distribution for fishing effort (right vertical axis) with (**a**) sea surface temperature (SST, °C), (**b**) chlorophyll-a (Chl-a, mg m^{-3}), (**c**) eddy kinetic energy (EKE, cm^{2}s^{-2}), (**d**) sea level anomalies (SLA, m), (**e**) sea surface Salinity (SSS, g kg^{-1}) of the squid ground in the western North Pacific (145–180° E, 35–50° N) during 2012–2020.

As shown in Figures 4 and 5, the latitudinal distribution centroid of the squid fishing ground during August to October was negatively correlated with the Kuroshio Extension index, which indicates a standardized mean high-frequency EKE within 142–149° E, 32–37° N. The value of the Pearson correlation coefficient between them is 0.57 ($p < 0.01$), which means that squid fishing activities shifted southwards as the Kuroshio Extension spread over a wider latitudinal band with a smaller Kuroshio Extension index. Conversely, when the Kuroshio Extension index was positive or greater, the Kuroshio Extension jet was weaker and more erratic, spreading over a wider latitudinal band, which would result in a northward shift in fishing activity (Figure 4).

3.4. El Niño and La Niña Events

As shown in Figure 4, El Niño events developed in May 1997–May 1998, June 2002–February 2003, July 2004–January 2005, September 2006–January 2007, April 2015–April 2016, October 2018–May 2019. La Niña events developed in July 1998–July 2000, September 2000–February 2001, November 2005–March 2006, July 2007–June 2008, August–December 2016, October 2017–April 2018, August 2020–April 2021.

For example, La Niña events (1st and 2nd La Niña events in 1998–2000, 3rd La Niña event in 2005, 6th La Niña event in 2012, 8th La Niña event in 2020) have been associated with a northward shift in the centers of gravity of fishing grounds and the distribution of fishing effort has shifted northwards to 43–44° N. In the years of El Niño events (2nd El Niño event 2002–2003, 3rd El Niño event 2004–2005, 6th El Niño event 2015–2016, 7th El Niño event 2019), the fishing grounds showed an obvious southward shift, in this case the fishing area moved southwards to 41.75–43° N (Figure 4).

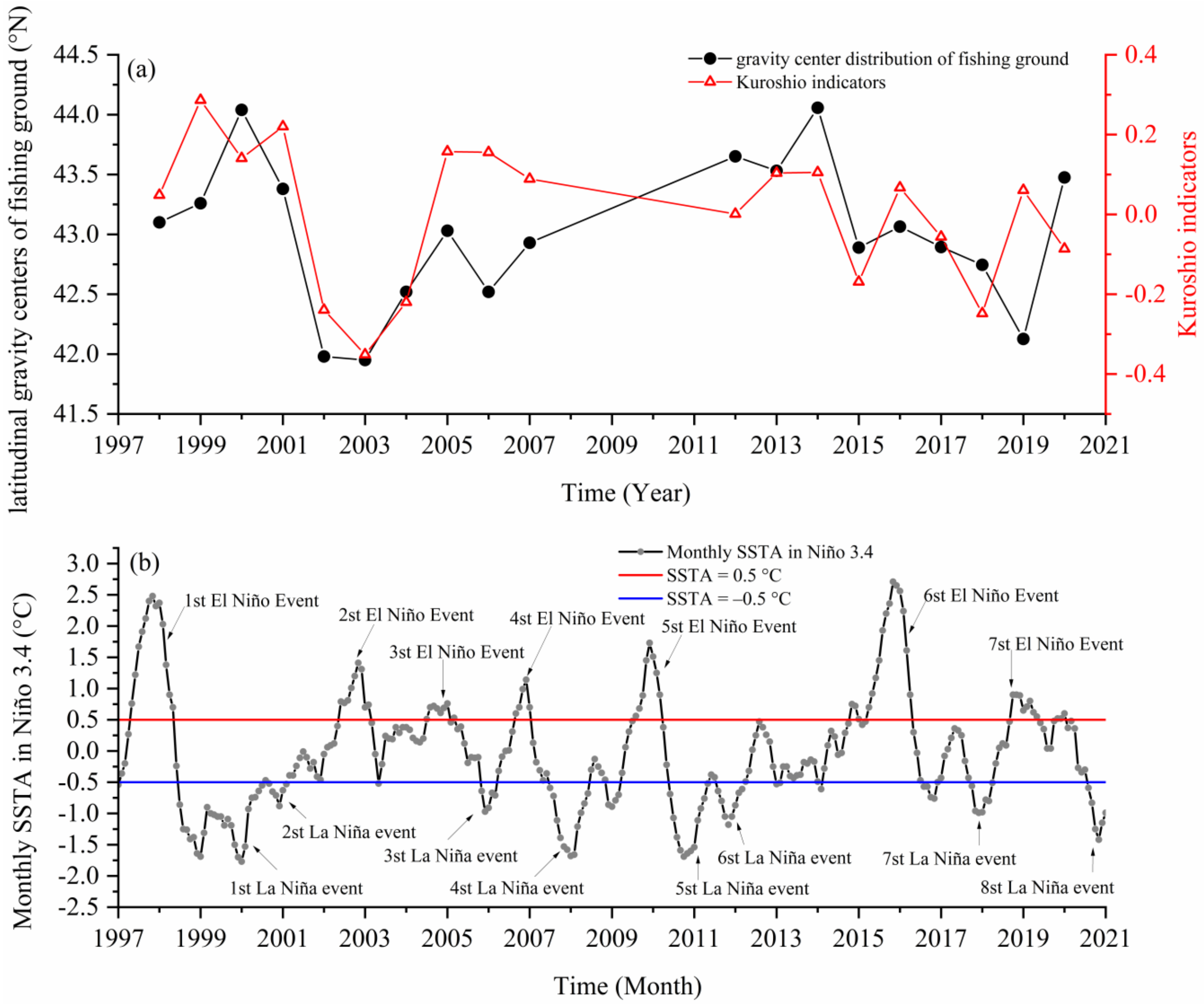

Figure 4. (**a**) Variations of the latitudinal gravity centers of fishing ground for squid jigger and mean Kuroshio indicators between August and October in the periods 1998–2007, 2012–2020; (**b**) Time-series of SSTA in the area of Niño 3.4, showing the timing of the El Niño and La Niña events, 1997–2020.

3.5. Relation between Kuroshio Indicators and the Number of Mesoscale Eddies

The number of the anticyclonic and cyclonic eddies generated from August to October during 1998–2007, and 2012–2020 varied between 216–260 (Figure 6). The changes in the numbers of mesoscale eddies generated in the squid fishing ground (35–50° N, 145–170° E), and Kuroshio indicators (within the 142–149° E and 32–37° N) followed the same trend. It is clear that the eddy number had a positive correlation with the Kuroshio Extension index (Figures 6 and 7), with the correlation coefficient between them being 0.62 ($p < 0.05$).

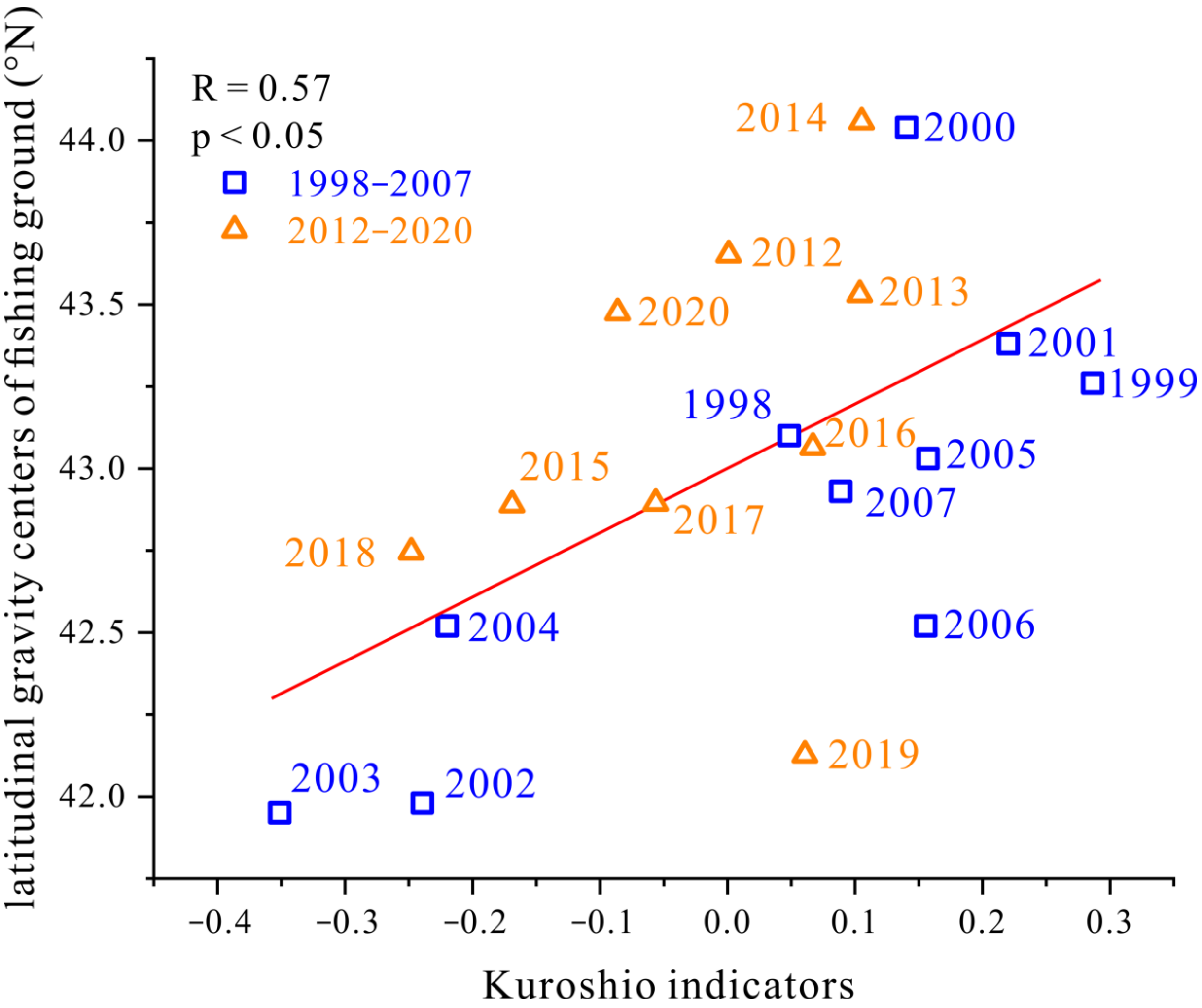

Figure 5. Relationship between the latitudinal gravity centers of fishing ground for squid jigger and mean Kuroshio indicators between August and October in the periods 1998–2007 (blue square), 2012–2020 (yellow triangle).

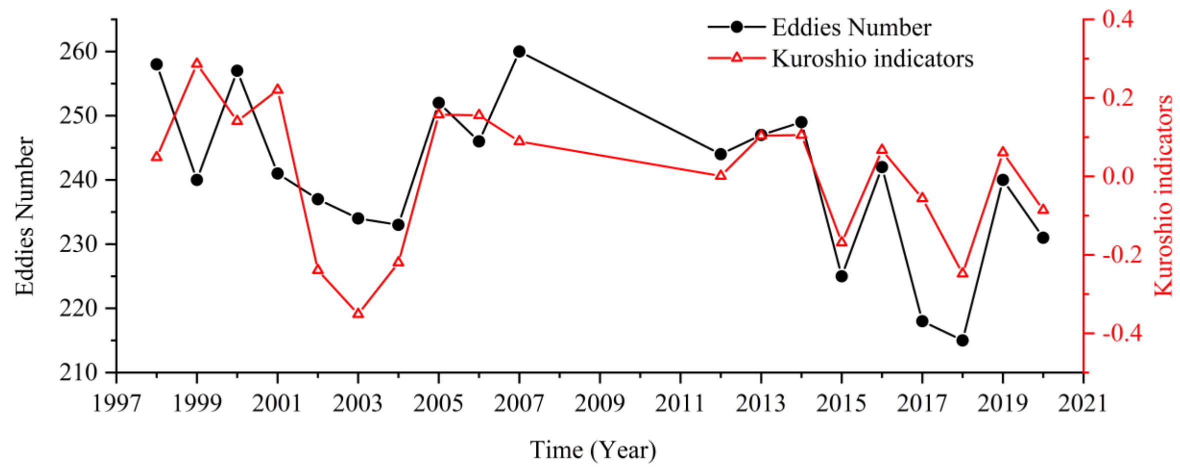

Figure 6. Variations of the number of anticyclonic and cyclonic eddies and mean Kuroshio indicators between August and October in the periods 1998–2007, 2012–2020.

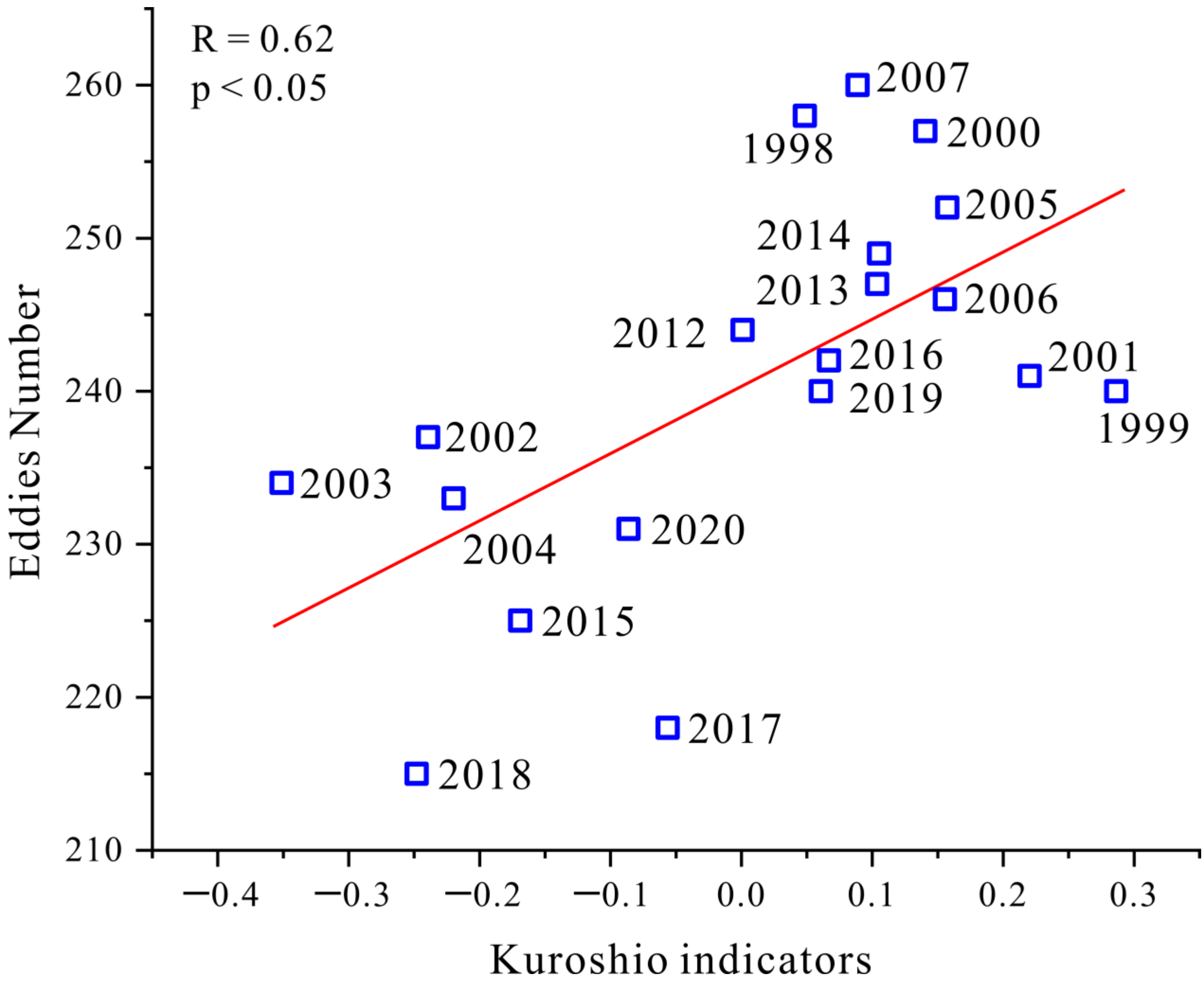

Figure 7. Relationship between the number of eddies generated in fishing ground for squid jigger and mean Kuroshio indicators between August and October in the periods 1998–2007, 2012–2020.

4. Discussion

4.1. Influence of El Niño/La Niña Events on the Distribution of Fishing Grounds

In this study, the Chinese squid jigging fishing activity was distributed between 36–48° N and 146–170° E, which is consistent with the traditional fishing area of the Chinese jigging fishery in the western North Pacific [24]. This result is also similar to the previous study that based on AIS [11].

Previous studies suggest that climatic events and variations in the marine environment would have significant impacts on the distribution and the abundance of squid [4,38]. The SSTA in the Niño 3.4 region was negatively correlated with the SSTA in the feeding grounds with a time lag of 3 months. SST in the feeding area would increase during a La Niño event, shifting high-yield fishing grounds further north; conversely, SST in the feeding grounds would decrease during El Niño events, shifting fishing grounds southward [4]. In this study, the latitudinal centers of gravity of the fishing ground was maintained further north due to the La Niña events in 1998–2001, 2012 and 2020 (Figure 3). As shown in Figure 3, SST anomalies in the Niño 3.4 region (5° N–5° S, 120–170° W) indicated warm episodes during the El Niño events in 2002–2004, 2015–2016, 2018–2019, when the latitudinal centers of gravity of the feeding ground obviously shifted southwards. These results confirm that climatic events have a significant impact on the feeding ground of the neon flying squid.

These El Niño/La Niña events affect the Kuroshio–Oyashio transition area through the temperature dynamics that modulated by the Kuroshio transport [24]. According to previous studies, the optimal ranges of the SST for suitable habitat area of *Ommastrephes bartramii* ranged between 15–20 °C [3,11,39]. In our study, the isothermal lines for 15 °C, 20 °C, and 23 °C were located at 46.83° N, 42.31° N and 40.68° N during the 6th La Niña event in September 2012 and shifted southward to 44.61° N, 39.56° N and 39.25° N during the 7th El Niño event in September 2019 (Figure 8). As an important factor affecting the distribution of the neon flying squid, the SST was strongly influenced by the El Niño/La Niña events and ultimately affected the feeding ground of the neon flying squid.

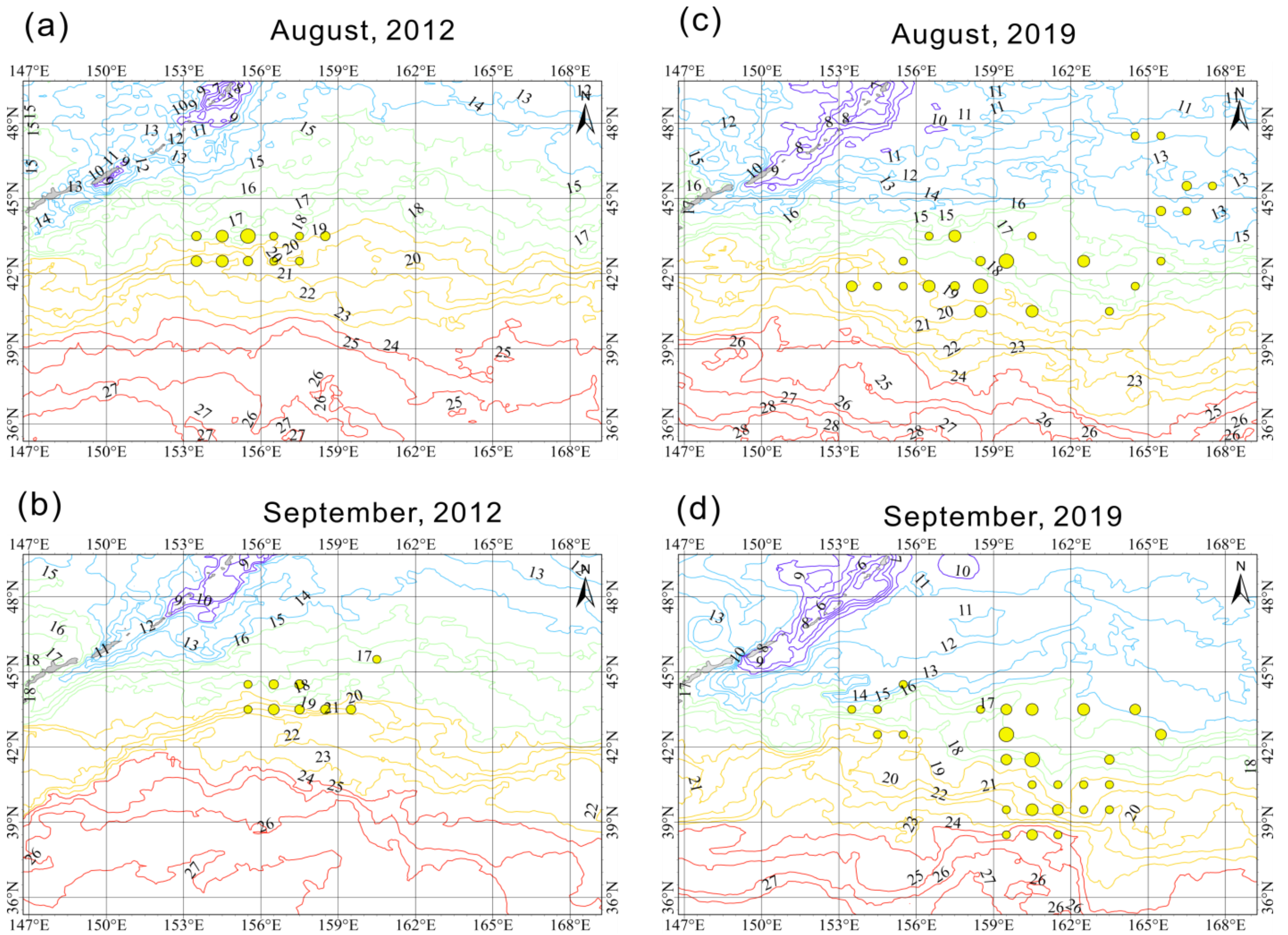

Figure 8. The distribution of the squid fishing area and isothermal lines in the Northwest Pacific in (**a**) August 2012, (**b**) September 2012, (**c**) August 2019, and (**d**) September 2019.

The Kuroshio Extension index showed similar trends with the latitudinal centers of gravity of the fishing ground, and in addition, the Kuroshio Extension index increased during La Niña events and decreased during El Niño events (Figure 3). Although the fishing ground was located in the Kuroshio–Oyashio transition area, the positive relationship between the latitudinal centroid of the fishing ground and the Kuroshio Extension indicator indicates that the feeding area of the neon flying squid *Ommastrephes bartramii* was affected by the upstream KE system.

4.2. Impact of the Kuroshio on the Distribution of Fishing Grounds

The higher values of the Kuroshio Extension index during La Niña events implied that the upstream Kuroshio (32–37° N, 142–149° E) was weaker and more unsteady, spreading over a wider latitudinal band, while the upstream KE path appeared more variable and meandering [37]. The unstable state of the upstream KE is characterized by high regional eddy kinetic energy (EKE) and strong eddy-shedding processes [37,40]. A previous study found that the SST anomalies in the Kuroshio–Oyashio transition area were mainly generated by the anticyclonic eddy activities that detached northward from the KE [41]. As the anticyclonic eddies (warm core) separated from the more convoluted KE path and moved northward, the SST anomalies in the Kuroshio–Oyashio Transition Area increased [41]. The isothermal lines for 10 °C, 15 °C, 23 °C shifted northward, and suitable habitats for neon fly squid moved northward with suitable thermal conditions.

On the contrary, the Kuroshio Extension index was small during El Niño events. At the same time, the upstream KE path was straight and characterized by low regional EKE and fewer anticyclonic eddies (warm core), which had led to negative SST anomalies in the Kuroshio–Oyashio transition area [41]. The thermal conditions suitable for habitats of neon fly squid shifted southward, accompanied by the shift of the fishing ground to the south.

The distribution type of the Kuroshio Bend, which occurred in 35–40° N, 140–150° E, had a significant relationship with the variation of the gravity center of the fishing ground for *Ommastrephes bartramii* in latitude [32]. The large bending (associated with the smaller value of the Kuroshio index) in the North Pacific (35–40° N, 140–150° E) corresponds to the change of the squid fishing ground with the latitudinal distribution centroid shifting to the further north. Conversely, a small bend (larger Kuroshio index) is associated with a more southerly latitudinal distribution centroid of the squid fishing ground. The meandering of the upstream Kuroshio is closely related to the contracted or elongated state, which can be indicated by the Kuroshio Extension index.

Furthermore, the positive correlation between the Kuroshio Extension index and the eddy number shows that the eddy number has varied decadally following the weakening or strengthening trends of the upstream KE. These results suggest that the regional eddy kinetic energy (EKE) level and eddy-shedding processes in the upstream KE have great influences on the transport and distribution of heat, salt, energy and Chl-a, and further lead to the dynamic changes of the fishing ground of *Ommastrephes bartramii*. For example, Igarashi et al. [12] and Zhang et al. [6] suggested that the warm eddies formed along the east coast of Japan may be responsible for the formation of the neon flying squid fishing ground.

This study shows that an inter-annual variation in the fishing ground of *Ommastrephes bartramii* could be modulated by the eddies associated with the states of the upstream KE. The Kuroshio index (mean high-frequency eddy kinetic energy between 32° and 37° N, 142° and 149° E) can be used as a good indicator of Kuroshio extension variations to investigate the fishing ground in the Kuroshio–Oyashio transition area.

It has been found that the distribution of squid is influenced by the vertical distribution of seawater temperatures in the North Pacific [3] and that warm eddies during periods of instability in the Kuroshio contribute to the formation of high squid production areas [6]. However, to understand the relationship between squid distribution, eddies and the Kuroshio, more research is needed to achieve quantitative analysis through modelling studies, e.g., adding the Kuroshio index as a factor in the model.

Supplementary Materials: The following supporting materials can be downloaded at: https://www.mdpi.com/article/10.3390/jmse11050966/s1, Table S1: The result of Shapiro-Wilk normality test for Kuroshio indicators, latitudinal gravity centers of fishing ground and eddies Number.

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Data Availability Statement: Publicly available datasets were analyzed in this study, Fishing effort for the jigging fishery data can be found here: http://www.globalfishingwatch.org, accessed on 1 June 2022; The SST and Chl-a data can be found here: http://sites.science.oregonstate.edu/ocean.productivity/, accessed on 1 June 2022. The SLA and EKE data can be found here: https://www.aviso.altimetry.fr, accessed on 1 June 2022. The SSTA data can be found here: https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php, accessed on 1 June 2022. The SSS data can be found here: http://msdc.qdio.ac.cn, accessed on 1 June 2022. The gravity center of squid ground during August, September and October in 1998–2007 are available in FAN, et al. [32].

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Jereb, P.; Roper, C.F.E. Cephalopods of the world. An annotated and illustrated catalogue of cephalopod species known to date. In *Myopsid and Oegopsid Squids*; Food And Agriculture Organization Of The United Nations: Rome, Italy, 2010; Volume 2, p. 605.
2. Bower, J.R.; Ichii, T. The red flying squid (*Ommastrephes bartramii*): A review of recent research and the fishery in Japan. *Fish. Res.* **2005**, *76*, 39–55. [CrossRef]
3. Wang, J.; Cheng, Y.; Lu, H.; Chen, X.; Lin, L.; Zhang, J. Water Temperature at Different Depths Affects the Distribution of Neon Flying Squid (*Ommastrephes bartramii*) in the Northwest Pacific Ocean. *Front. Mar. Sci.* **2022**, *8*, 741620. [CrossRef]
4. Chen, X.J.; Zhao, X.H.; Chen, Y. Influence of El Niño/La Niña on the western winter–spring cohort of neon flying squid (*Ommastrephes bartramii*) in the northwestern Pacific Ocean. *ICES J. Mar. Sci.* **2007**, *64*, 1152–1160. [CrossRef]
5. Chen, X.; Liu, B.; Chen, Y. A review of the development of Chinese distant-water squid jigging fisheries. *Fish. Res.* **2008**, *89*, 211–221. [CrossRef]
6. Zhang, Y.; Yu, W.; Chen, X.; Zhou, M.; Zhang, C. Evaluating the impacts of mesoscale eddies on abundance and distribution of neon flying squid in the Northwest Pacific Ocean. *Front. Mar. Sci.* **2022**, *9*, 862273. [CrossRef]
7. Dong, E.; Shi, S.; He, J.; Tang, F. On state of squid jigging fishery and professional upgrading transformation of squid fishing vessels in the North Pacific—Take China Aquatic Products Zhoushan Marine Fisheries Co., LTD as an example. *Fish. Inf. Strategy* **2020**, *35*, 208–215. [CrossRef]
8. Yatsu, A.; Midorikawa, S.; Shimada, T.; Uozumi, Y. Age and growth of the neon flying squid, *Ommastrephes bartrami*, in the North Pacific ocean. *Fish. Res.* **1997**, *29*, 257–270. [CrossRef]
9. Watanabe, H.; Kubodera, T.; Ichii, T.; Sakai, M.; Moku, M.; Seitou, M. Diet and sexual maturation of the neon flying squid *Ommastrephes bartramii* during autumn and spring in the Kuroshio–Oyashio transition region. *J. Mar. Biol. Assoc. United Kingd.* **2008**, *88*, 381–389. [CrossRef]
10. Alabia, I.D.; Saitoh, S.-I.; Mugo, R.; Igarashi, H.; Ishikawa, Y.; Usui, N.; Kamachi, M.; Awaji, T.; Seito, M. Seasonal potential fishing ground prediction of neon flying squid (*Ommastrephes bartramii*) in the western and central North Pacific. *Fish. Oceanogr.* **2015**, *24*, 190–203. [CrossRef]
11. Fei, Y.; Yang, S.; Fan, W.; Shi, H.; Zhang, H.; Yuan, S. Relationship between the Spatial and Temporal Distribution of Squid-Jigging Vessels Operations and Marine Environment in the North Pacific Ocean. *J. Mar. Sci. Eng.* **2022**, *10*, 550. [CrossRef]
12. Igarashi, H.; Saitoh, S.-I.; Ishikawa, Y.; Kamachi, M.; Usui, N.; Sakai, M.; Imamura, Y. Identifying potential habitat distribution of the neon flying squid (*Ommastrephes bartramii*) off the eastern coast of Japan in winter. *Fish. Oceanogr.* **2018**, *27*, 16–27. [CrossRef]
13. Yu, W.; Chen, X. Habitat suitability response to sea-level height changes: Implications for Ommastrephid squid conservation and management. *Aquac. Fish.* **2021**, *6*, 309–320. [CrossRef]
14. Chen, X.; Tian, S.; Liu, B.; Chen, Y. Modeling a habitat suitability index for the eastern fall cohort of *Ommastrephes bartramii* in the central North Pacific Ocean. *Chin. J. Oceanol. Limnol.* **2011**, *29*, 493–504. [CrossRef]
15. Ichii, T.; Mahapatra, K.; Sakai, M.; Wakabayashi, T.; Okamura, H.; Igarashi, H.; Inagake, D.; Okada, Y. Changes in abundance of the neon flying squid *Ommastrephes bartramii* in relation to climate change in the central North Pacific Ocean. *Mar. Ecol. Prog. Ser.* **2011**, *441*, 151–164. [CrossRef]
16. Sasai, Y.; Richards, K.J.; Ishida, A.; Sasaki, H. Effects of cyclonic mesoscale eddies on the marine ecosystem in the Kuroshio Extension region using an eddy-resolving coupled physical-biological model. *Ocean Dyn.* **2010**, *60*, 693–704. [CrossRef]
17. McGillicuddy, D.J. Mechanisms of Physical-Biological-Biogeochemical Interaction at the Oceanic Mesoscale. *Annu. Rev. Mar. Sci.* **2016**, *8*, 125–159. [CrossRef]
18. Mahadevan, A. Eddy effects on biogeochemistry. *Nature* **2014**, *506*, 168–169. [CrossRef]
19. Ueno, H.; Bracco, A.; Barth, J.A.; Budyansky, M.V.; Hasegawa, D.; Itoh, S.; Yong Kim, S.; Ladd, C.; Lin, X.; Park, Y.-G.; et al. Review of oceanic mesoscale processes in the North Pacific: Physical and biogeochemical impacts. *Prog. Oceanogr.* **2023**, *212*, 102955. [CrossRef]
20. Wang, W.; Zhou, C.; Shao, Q. An application of RS/GIS on study on the migration dynamics of *Ommastrephes bartramii*. *High Technol. Lett.* **2003**, *11*, 90–93. (In Chinese)
21. Chen, X.; Tian, S.; Guan, W. Variations of oceanic fronts and their influence on the fishing grounds of *Ommastrephes bartramii* in the Northwest Pacific. *Acta Oceanol. Sin.* **2014**, *33*, 45–54. [CrossRef]

22. Chen, X.; Qian, W.; Xu, L.; Tian, S. Study on *Ommastrephe bartrami* fishing ground and forecasting model from 150° E to 165° E in the North Pacific Ocean. *Mar. Fish. Res.* **2003**, *24*, 1–6. (In Chinese)
23. Shao, Q.; Ma, W.; Chen, Z.; You, Z.; Wang, W. Relationship between Kuroshio meander pattern and *Ommastrephes bartramii* CPUE in northwest Pacific Ocean. *Oceanol. Limnol. Sin.* **2005**, *36*, 111–122.
24. Chen, X.; Cao, J.; Chen, Y.; Liu, B.; Tian, S. Effect of the Kuroshio on the Spatial Distribution of the Red Flying Squid *Ommastrephes Bartramii* in the Northwest Pacific Ocean. *Bull. Mar. Sci.* **2012**, *88*, 63–71. [CrossRef]
25. Talley, L.D. Distribution and Formation of North Pacific Intermediate Water. *J. Phys. Oceanogr.* **1993**, *23*, 517–537. [CrossRef]
26. Mizuno, K.; White, W.B. Annual and Interannual Variability in the Kuroshio Current System. *J. Phys. Oceanogr.* **1983**, *13*, 1847–1867. [CrossRef]
27. Qiu, B.; Chen, S. Variability of the Kuroshio Extension Jet, Recirculation Gyre, and Mesoscale Eddies on Decadal Time Scales. *J. Phys. Oceanogr.* **2005**, *35*, 2090–2103. [CrossRef]
28. Qiu, B.; Chen, S.; Schneider, N.; Taguchi, B. A Coupled Decadal Prediction of the Dynamic State of the Kuroshio Extension System. *J. Clim.* **2014**, *27*, 1751–1764. [CrossRef]
29. Nonaka, M.; Sasaki, H.; Taguchi, B.; Schneider, N. Atmospheric-Driven and Intrinsic Interannual-to-Decadal Variability in the Kuroshio Extension Jet and Eddy Activities. *Front. Mar. Sci.* **2020**, *7*, 547442. [CrossRef]
30. Qiu, B.; Chen, S. Eddy-mean flow interaction in the decadally modulating Kuroshio Extension system. *Deep Sea Res. Part II Top. Stud. Oceanogr.* **2010**, *57*, 1098–1110. [CrossRef]
31. Kroodsma, D.A.; Mayorga, J.; Hochberg, T.; Miller, N.A.; Boerder, K.; Ferretti, F.; Wilson, A.; Bergman, B.; White, T.D.; Block, B.A.; et al. Tracking the global footprint of fisheries. *Science* **2018**, *359*, 904–908. [CrossRef]
32. Fan, J.; Chen, X.; Cao, J.; Tian, S.; Qian, W.; Liu, B. The variation of fishing ground of *Ommastrephes bartramii* in the Northwest Pacific concerning with Kuroshio current. *J. Shanghai Ocean Univ.* **2010**, *19*, 378–384.
33. Cheng, L.; Trenberth, K.E.; Fasullo, J.; Boyer, T.; Abraham, J.; Zhu, J. Improved estimates of ocean heat content from 1960 to 2015. *Sci. Adv.* **2017**, *3*, e1601545. [CrossRef] [PubMed]
34. Chelton, D.B.; Schlax, M.G.; Samelson, R.M. Global observations of nonlinear mesoscale eddies. *Prog. Oceanogr.* **2011**, *91*, 167–216. [CrossRef]
35. Chelton, D.B.; Schlax, M.G.; Samelson, R.M.; de Szoeke, R.A. Global observations of large oceanic eddies. *Geophys. Res. Lett.* **2007**, *34*, L15606. [CrossRef]
36. Schlax, M.G.; Chelton, D. *The "Growing Method" of Eddy Identification and Tracking in Two and Three Dimensions*; College of Earth, Ocean and Atmospheric Sciences, Oregon State University: Corvallis, OR, USA, 2016.
37. Bessières, L.; Rio, M.H.; Dufau, C.; Boone, C.; Pujol, M.I. Ocean state indicators from MyOcean altimeter products. *Ocean Sci.* **2013**, *9*, 545–560. [CrossRef]
38. Sakurai, Y.; Kiyofuji, H.; Saitoh, S.; Goto, T.; Hiyama, Y. Changes in inferred spawning areas of *Todarodes pacificus* (*Cephalopoda*: *Ommastrephidae*) due to changing environmental conditions. *ICES J. Mar. Sci.* **2000**, *57*, 24–30. [CrossRef]
39. Tian, S.; Chen, X.; Chen, Y.; Xu, L.; Dai, X. Evaluating habitat suitability indices derived from CPUE and fishing effort data for *Ommatrephes bratramii* in the northwestern Pacific Ocean. *Fish. Res.* **2009**, *95*, 181–188. [CrossRef]
40. Yang, H.; Qiu, B.; Chang, P.; Wu, L.; Wang, S.; Chen, Z.; Yang, Y. Decadal Variability of Eddy Characteristics and Energetics in the Kuroshio Extension: Unstable Versus Stable States. *J. Geophys. Res. Ocean.* **2018**, *123*, 6653–6669. [CrossRef]
41. Sugimoto, S.; Hanawa, K. Roles of SST Anomalies on the Wintertime Turbulent Heat Fluxes in the Kuroshio–Oyashio Confluence Region: Influences of Warm Eddies Detached from the Kuroshio Extension. *J. Clim.* **2011**, *24*, 6551–6561. [CrossRef]