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Fishing Ground Distribution of Neon Flying Squid (*Ommastrephes bartramii*) in Relation to Oceanographic Conditions in the Northwest Pacific Ocean

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Abstract Neon flying squid, *Ommastrephes bartramii*, is a squid species of the North Pacific Ocean, which plays an important economical role in the international fishery. Logbook data for Chinese squid-jigging fishery over 2004–2011 were used to evaluate the relationship between the fishing grounds of the squid and the convergent frontal areas, which were defined by the contour lines of specific sea surface temperature (SST) and chlorophyll-*a* (Chl-*a*) concentration. Our results indicate that the SST in the range of 15 to 19℃ and the Chl-*a* concentration in the range of 0.1 to 0.4 mg m^{-3} are the favorable conditions for the aggregation of the squid. Additionally, we deduced that the SST at 17.5℃ and the Chl-*a* concentration at 0.25 mg m^{-3} are the optimal environmental conditions for the aggregation of *O. bartramii*. In August, the annual CPUE is positively correlated with the proportion of the fishing grounds with favorable SST and Chl-*a* concentration, as well as the combination of the two variables, implying that the abundance of the squid annually is largely depending on the presence of the favorable environmental conditions for fishery in August. Minor spatial difference between mean latitudinal location of the 17.5℃ SST and 0.25 mg m^{-3} Chl-*a* fronts can increase the CPUEs of *O. bartramii*. Furthermore, the monthly latitudinal gravity centers of the CPUE closely followed the mean latitudinal position of the contour lines of the 17.5℃ SST and the 0.25 mg m^{-3} Chl-*a* concentration. Our findings suggest the convergent oceanographic features (fronts) play significant roles in regulating the distribution and abundance of the western stock of the winter-spring cohort of *O. bartramii*, which can help people to improve their ability to discover the *O. bartramii* fishing grounds with higher productivity.

Key words neon flying squid; sea surface temperature; chlorophyll-*a*; oceanic fronts; fishing ground; the Northwest Pacific Ocean

1 Introduction

The Northwest Pacific Ocean is one of the most productive water areas in the world, contributing to many important fishing grounds (Kim, 2010). The Kuroshio and Oyashio Ecosystem (KOE) forms the Transition Zone (TZ) between the Subtropical Front and the Subarctic Front (Roden, 1991), which creates an important habitat for many commercial pelagic fish species to spawn, migrate, and feed, including Pacific saury (*Cololabis saira*), skipjack tuna (*Katsuwonus pelamis*), Japanese sardine (*Sardinops melanostictus*) (Tian *et al*., 2003; Nishikawa *et al*., 2011; Lehodey *et al*., 2013) and some squid species that have a short life cycle (Bower and Ichii, 2005; Kawabata *et al*., 2006). Some strong correlations have been found between the physical and chemical conditions of the TZ and the population dynamics of the pelagic fish species, and such relationships have largely attributed to the complex oceanographic features of the region such as oceanic fronts and eddies (Tseng *et al*., 2013; Chen *et al*., 2014).

In the North Pacific, the population of neon flying squid, *Ommastrephes bartramii*, comprises a winter-spring cohort and an autumn cohort (Bower and Ichii, 2005). Both are widely distributed in the temperate waters between 20°N and 50°N (Roper *et al*., 1984). Due to the great economic importance of this species, squid-jigging fishing vessels from many countries are attracting to here to operate in the regions of the Northwest and Central Pacific Ocean, especially the Northeast Asian countries such as Japan, Russia, Korea and China (Chen *et al*., 2008). The winter-spring cohort of *O. bartramii* is geographically divided into a western and a central stock, with the former as the main fishing target of the Chinese squid-jigging fishery in the Northwest Pacific Ocean (Wang and Chen, 2005). Mainland China have begun to

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harvest *O. bartramii* since 1993, and later the industry expanded into much larger scale with major fishing season lasting from July to November. The production of *O. bartramii* in China reached its peak in 1999 with 132000 tons of captures, but the annual *O. bartramii* production fluctuated greatly in recent years, with a major decline in 2009 when the production dropped to merely 36000 tons (Yu *et al*., 2015a).

The migratory range of the species of *O. bartramii* is very long, where the northward migration starts from the southern spawning grounds during winter, and ends at the northern feeding grounds in summer (Fig.1; Murata and Nakamura, 1998). It is well established that the spatio-temporal distributions of *O. bartramii* are closely related to the varied environmental conditions of the fishing grounds (Yu *et al*., 2015b). The migration as well as the aggregation of *O. bartramii* towards their preferred habitats tend to be encouraged by the optimal physical and chemical conditions of the environment (Alabia *et al*., 2015). Previous studies have suggested that the surface water temperature and the availability of the food play an important role in regulating squid aggregation (Chen and Chiu, 2003; Ichii *et al*., 2009). Sea surface temperature (SST) is a crucial environmental factor of the squid fishing grounds (Chen and Chiu, 1999). Chen *et al*. (2007) examined the SST of the feeding grounds of the winter-spring cohort of *O. bartramii* under anomalous climatic conditions. It was observed that under a La Niña event the SST of the feeding grounds will rise, and the squids tend to aggregate farther north as the optimal SST for squid schoolings to be ranged between 16℃ and 19℃. An El Niño event would lead to a decrease in the SST and a southward shift of the fishing grounds with the optimal SST of 14–17℃. Additionally, the winter location of the Transition Zone Chlorophyll Front (TZCF) in the nursery grounds significantly influences the abundance of the autumn cohort of *O. bartramii*, and which can be used to predict the changes of the catch-per-unit-effort (CPUE) (Ichii *et al*., 2011). For the winter-spring cohort of *O. bartramii*, the favorable chlorophyll-*a* (Chl-*a*) concentration in the fishing grounds varied in the range from 0.1 to 0.6 mg m^{-3} (Fan *et al*., 2009). Varied Chl-*a* concentration of the spawning grounds could also cause interannual variability of the CPUE as well (Nishikawa *et al*., 2014).

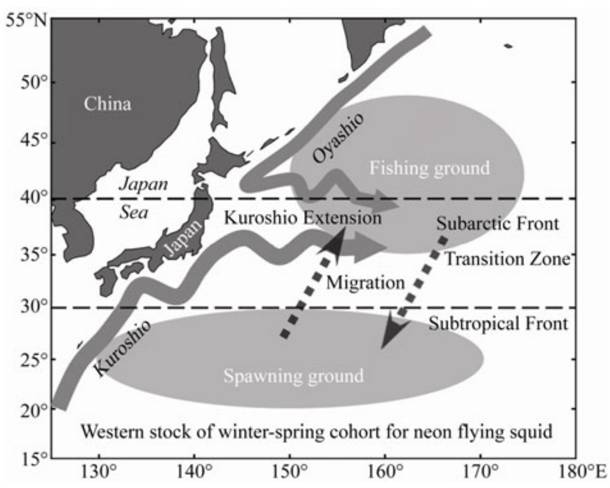

Fig.1 Map of the geographical distribution of the western stock of the winter-spring cohort of *Ommastrephes bartramii* in the Northwest Pacific Ocean with the oceanographic features.

In previous studies, researchers have evaluated the effects of the SST and the Chl-*a* concentration on the *O. bartramii* stock (Yu *et al*., 2015b). However, additional factors such as the ocean color and thermal fronts can also be a key to determine potential productive habitats of the pelagic fish species (Montgomery *et al*., 1986). For example, Zainuddin *et al*. (2004) used satellite data of the SST and the Chl-*a* concentration to identify the fishing grounds of albacore (*Thunnus alalunga*). In the locations close to the convergence of the 20℃ SST and 0.3 mg m^{-3} Chl-*a* fronts, the CPUEs of albacore tends to increase significantly, and which bring up some interesting questions regarding how the convergence of oceanographic features like the front areas of SST and Chl-*a* can affect the abundance of the target species or whether the shift of squid fishing grounds is driven by the physiologically suitable temperature of the species only or in conjunction with the availability of the food sources. All of these questions have not yet been explored for *O. bartramii* in the past.

In our current study, we hypothesize that the locations of the most productive habitat of the squid *O. bartramii* are associated with the confluence areas of the SST and Chl-*a* concentration fronts. Thus, we are attempting to determine the favorable environmental conditions for the aggregation of the squid, as well as to further examine the relationship between the location of the gravity centers of CPUE and that of the frontal areas. The purpose of this study is to establish the spatio-temporal dynamic relationship between the distribution and aggregation of the western winter-spring cohort of *O. bartramii* and the optimal combining effects of the temperature and the chlorophyll fronts. Such a study can improve our ability to explore potential fishing grounds of *O. bartramii* for higher fishery production.

2 Materials and Methods

2.1 Fishery Data

The logbooks of commercial squid-jigging vessels from 2004 to 2011 were collected by Chinese Squid-jigging Science and Technology Group from the Shanghai Ocean University. China counted more than 80% of the total squid catches in the Northwest Pacific Ocean (Wang and Chen, 2005). Fishing operations carried out on each vessel were recorded, including the information on the tonnage of the catch (in tons) and the fishing effort (the duration of the fishing in days) as well as the locations (latitude and longitude) and the time (year and month) of the fishing operations. Most fishing vessels were operating on the fishing grounds at the location between 37˚–46˚N and 150˚–175˚E in the Northwest Pacific Ocean region from July to November, with the western stock of winter-spring cohort of *O. bartramii* as the target. All of the

Chinese squid-jigging fishing vessels in the database were equipped with same engines powers (Chen *et al*., 2007; Cao *et al*., 2009). The nominal CPUE of each month (unit: $t\,d^{-1}$) was calculated and the average number was plotted on a 1˚×1˚ latitude/longitude grid, which was considered as a reliable index indicator to evaluate the abundance of the squids at that area in this study.

2.2 The Data of Environmental Conditions

The monthly SST data were obtained from the National Oceanic and Atmospheric Administration (NOAA) High-resolution Blended Analysis dataset at 1˚×1˚ resolution (http://apdrc.soest.hawaii.edu/data). The data of the monthly MODIS Chl-*a* concentration were obtained from the Live Access Server of National Oceanic and Atmospheric Administration Ocean Watch (http://oceanwatch.pifsc.noaa.gov/las/servlets/dataset) at the resolution of 0.1 grid. The data of the environmental conditions cover the fishing grounds and the fishing seasons from July to November over the period of 2004–2011. Furthermore, all the data of the environmental conditions were re-gridded to the same resolution in order to match with the collected fishery data.

2.3 The Distribution of *O. bartramii* in Relation to the Environmental Conditions

In this study, the most suitable ranges of the SST and the Chl-*a* concentration for the distribution of *O. bartramii* were evaluated through histogram analysis (Zainuddin *et al*., 2006). Both the data of CPUE and fishing effort were analyzed in order to determine the most suitable range of each individual environmental variable. Based on the data of the total CPUE and the distribution frequency map of the fishing effort with regard to each environmental variable, we analyzed their relationship in order to accurately estimate the most suitable environmental conditions for the most productive habitat of *O. bartramii*. The optimal ranges of the SST and the Chl-*a* concentration were determined based on the median values with the highest histogram frequency from the data of the CPUE and fishing effort in a given interval of each variable, and which were considered as the best candidate as productive habitats of *O. bartramii*.

Based on the histogram analysis, a specific range of the SST and the Chl-*a* concentration were selected and used to define the suitable habitats that are favorable for squid aggregation. We were trying to link the annual CPUE with the environmental variables in each month to evaluate the relationship between the abundance of the squid and the environmental conditions. Therefore, the correlations between the fishery data (annual CPUE) and the proportion of the favorable-SST and Chl-*a* concentration or the combining effects of the two factors in fishery areas each month were analyzed. In this study, we used two methods to calculate the combining effects of the favorable environmental factors for the fishery: 1) the square root of the proportion of the areas with favorable SST and Chl-*a* concentration in the study region; 2) the average of the proportion of the areas with the two favorable factors covering the fishing grounds (Yu *et al*., 2016).

In addition, the optimal values of the preferred SST and Chl-*a* concentration were combined in order to estimate the spatio-temporal variations of the frontal areas as well as to evaluate its relationship with the potential productive *O. bartramii* fishing grounds from July to November during the period of 2004–2011. The latitudinal distributions of squid fishing grounds were also used to compare with the latitudinal locations of the frontal areas. The mean latitudinal position of the optimal SST and Chl-*a* contour lines between 150˚E and 175˚E was calculated by Matlab software. The latitudinal gravity center of the nominal CPUE in month *m* was obtained by the following equation (Chen *et al*., 2012):

$$LATG_m = \frac{\sum_{i=1}^{K}(LATG_i \times CPUE_{mi})}{\sum_{i=1}^{K} CPUE_{mi}},$$

where $LATG_m$ is the latitudinal gravity centers of nominal CPUE in month m; $LATG$ is the latitudinal mid-point of the ith area; $CPUE_{mi}$ is the nominal CPUE in area i in month m; K is the number of total fishing units.

3 Results

3.1 Temporal Variability of the CPUE, Fishing Effort and Environmental Variables

During the period of 2004–2011, the annual catch and CPUE of *O. bartramii* in the Northwest Pacific Ocean regions showed significant interannual variability (Fig.2). Each year, the catch was more than 100000 tons during the period of 2004–2008 with the highest catch at 113117 tons in 2007, but it dropped drastically to less than 60000 tons over the period of 2009–2011. The records of annual CPUE varied with the same trend as that of the annual catch, ranging from $1.36\,t\,d^{-1}$ in 2009 to $4.17\,t\,d^{-1}$ in 2007.

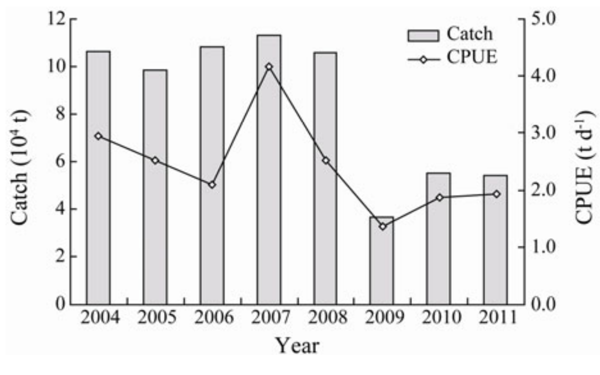

Fig.2 Annual catch and catch per unit effort (CPUE) of the western winter-spring squid stock for Chinese squid-jigging fishery over 2004–2011.

Monthly average CPUE, the fishing effort and the environmental variables were shown in Fig.3 for the period of 2004–2011. A high frequency distribution map of fishing effort (>20% of the total fishing efforts) was shown during the months between July and October. However, in November, the fishing effort frequency decreased drastically, and which constituted for less than 10% of the total fishing efforts. The CPUE reached its maximum at 3.13 t d^{-1} in August, and closely followed by September at 2.92 t d^{-1}, but the CPUEs of July and November were still relatively low. Higher CPUEs tended to be consistently associated with relatively warmer SST and more suitable surface Chl-*a* concentration. The average SSTs and Chl-*a* concentrations of the fishing grounds in August and September were about 20.3℃ and 0.29 mg m^{-3}, and 20.6℃ and 0.28 mg m^{-3}, respectively. Comparing to the other months, SSTs were found to be lower in July and November while the Chl-*a* concentrations tended to be higher.

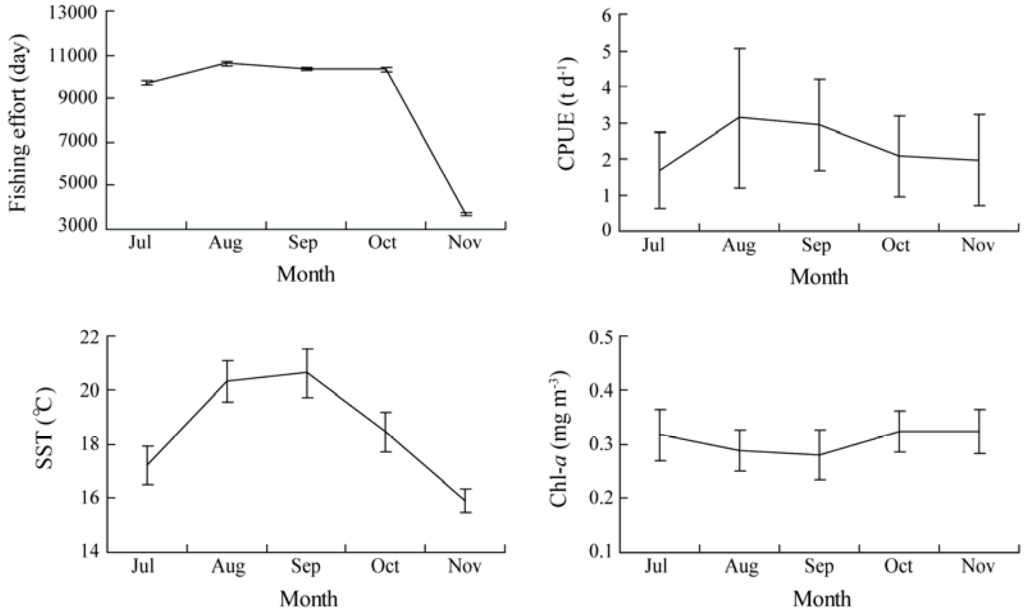

Fig.3 Monthly variations of the fishing effort frequency, CPUE, sea surface temperature (SST) and chlorophyll-*a* (Chl-*a*) concentration on the fishing grounds from July to November during 2004–2011.

3.2 The Relationship of the Fishing Ground Distributions and the Environmental Conditions

In Fig.4, we can see that almost all of the fishing efforts were occurred in areas where the range of SST varied from 9 to 23℃ and that of the Chl-*a* concentration varied from 0.1 to 1.7 mg m^{-3} (Fig.4). However, the majority of the fishing efforts were occurred in the fishing grounds with SST ranging from 15 to 19℃, and the histogram analysis of the fishing effort showed that the highest frequency occurred at the SST of 17.5℃. A similar trend was observed in the data of the total CPUE as that of the SST. Higher CPUE occurred in the waters where the SST was between 15 and 19℃ with the highest

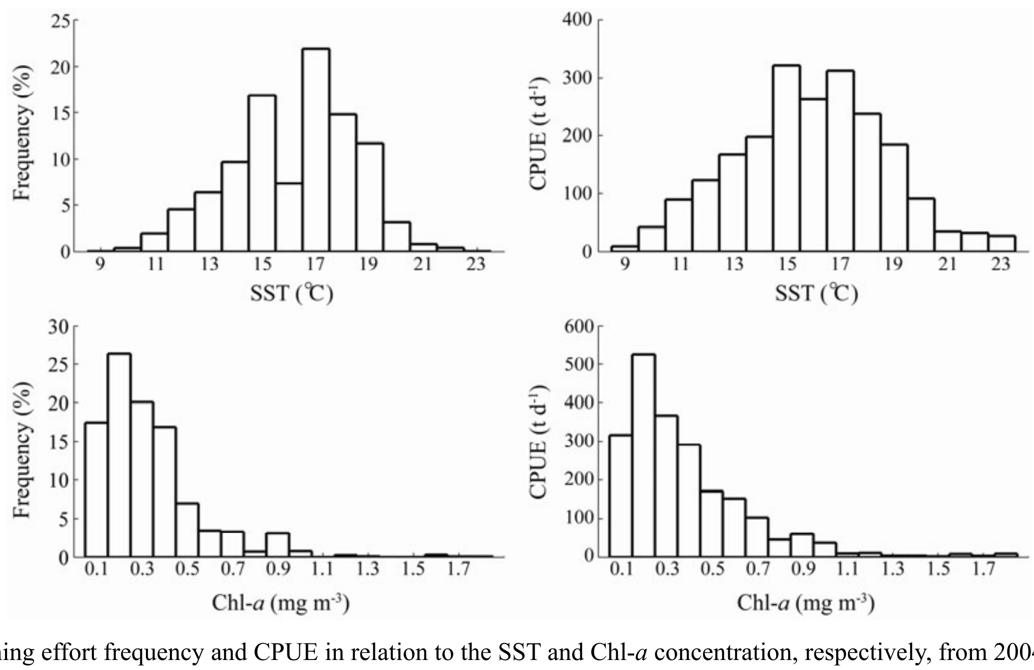

Fig.4 Fishing effort frequency and CPUE in relation to the SST and Chl-*a* concentration, respectively, from 2004 to 2011.

CPUE occurring at the SST of 15.5℃. However, the nominal CPUE was also quite high at the SST of 17.5℃, so 17.5℃ was considered as the optimal SST for the abundance of *O. bartramii*. As for the Chl-*a* concentration, both histograms showed that the high frequency fishing efforts and the higher CPUEs appeared in the waters with 0.1 to 0.4 mg m^{-3} Chl-*a*. The highest CPUE and fishing efforts occurred at the Chl-*a* of 0.25 mg m^{-3}, so the optimal Chl-*a* concentration was chosen to be 0.25 mg m^{-3} (Fig.4).

Correlation analysis found no significant relationship of the abundance of *O. bartramii* (annual CPUE) with fishery-favorable SST and Chl-*a* concentration, or with the areas that had both the two favorable factors in July, September, October, and November except for the fishery-favorable Chl-*a* concentration in October (Table 1). However, during August, the annual CPUE was positively correlated with the part of the fishing grounds that occupied the areas with favorable SST and Chl-*a* concentration individually, as well as together.

Table 1 Correlation (*r* value) between the annual catch of *Ommastrephes bartramii* per unit effort (CPUE) and the fishery-favorable area in the Northwest Pacific Ocean during 2004–2011

Variable	July		August		September		October		November	
	r	*P*	*r*	*P*	*r*	*P*	*r*	*P*	*r*	*P*
SST	0.319	n.s.	0.684	*	0.153	n.s.	0.159	n.s.	−0.505	n.s.
Chl-*a*	−0.377	n.s.	0.674	*	−0.145	n.s.	−0.719	*	−0.224	n.s.
$\sqrt{\text{SST}\times\text{Chl-}a}$	0.037	n.s.	0.767	*	0.000	n.s.	−0.442	n.s.	−0.426	n.s.
0.5×(SST+Chl-*a*)	−0.091	n.s.	0.758	*	−0.064	n.s.	−0.607	n.s.	−0.354	n.s.

Notes: *: $P<0.05$. n.s.: not significant.

3.3 The Effects of the Optimal SST and Chl-*a* Concentration on the Abundance and Distribution of *O. bartramii*

Specific SST at 17.5℃ and Chl-*a* at 0.25 mg m^{-3} were used as the optimal indicating factors for exploring the most productive fishing grounds of *O. bartramii*. In Fig.5, we evaluated the mean latitudinal positions of the SST at 17.5℃ and the Chl-*a* concentration at 0.25 mg m^{-3} each month on the contour lines from the latitude 150˚ to 175˚E. It was noted that the high abundance of the squids was associated with a short distance on the difference of the latitudinal position between the optimal SST and Chl-*a* concentration, and this phenomenon was particularly prominent from August to October. For example, some shorter distances of the mean difference latitudinal position were recorded for 0˚N the August of 2004, for 0.4˚N in the September of 2005, 0.4˚N in the August of 2007, 0.3˚N in the October of 2007, 0.2˚N in the September of 2008, and 0.3˚N in the August of 2010, corresponding to the relatively high CPUEs of 5.53, 3.77, 6.17, 3.07, 3.45 and 2.35 t d^{-1}, respectively. Conversely, almost all of the lower CPUEs that appeared in July and November were consistently associated with a longer distance of the mean difference of the latitudinal position between the two factors. Regression analysis also confirmed that the CPUE was negatively associated with the distance of the mean difference of the latitudinal position between the contour lines of the 17.5℃ SST and the 0.25 mg m^{-3} Chl-*a* concentration (F=12.172, R^2=0.243, $P<0.01$).

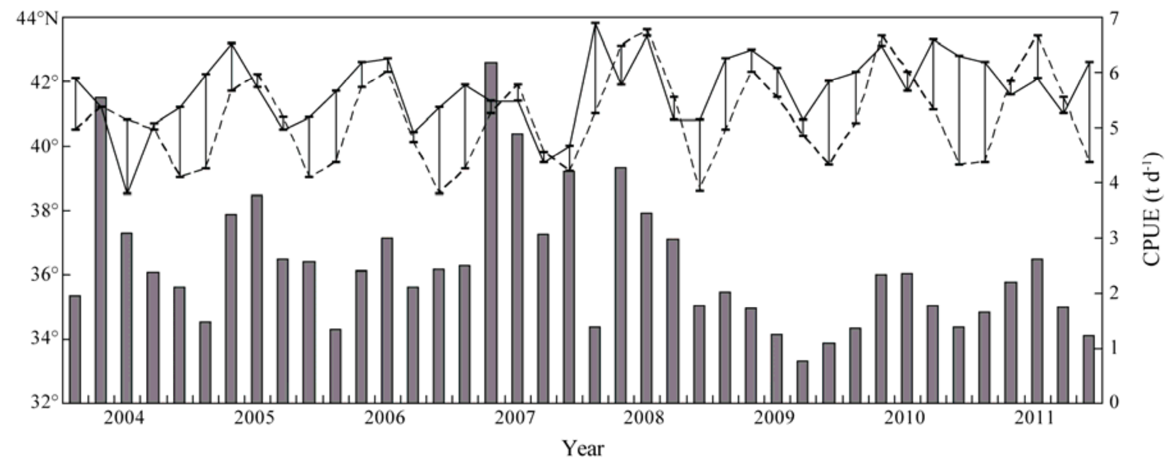

Fig.5 Variability in the distance between monthly mean latitudinal position between the 17.5℃ SST isotherm (the dotted line) and 0.25 mg m^{-3} Chl-*a* isoline (the solid line) from the latitude of 150˚ to 175˚E and the monthly CPUE (the bar) through July to November over 2004–2011.

The monthly average distance of mean latitudinal position between the two indicating factors varied from July to November (Fig.6). Spatial distances of the mean position of the two contour lines were much smaller from August to October than that in July and November with the difference of more than 2.3˚N. In Fig.7, we further compared the latitudinal gravity centers of CPUE with the mean latitude of 17.5℃ SST isotherm and 0.25 mg m^{-3}

Chl-*a* isoline on the fishing grounds in the Northwest Pacific from July to November over 2004–2011 (Fig.7). The results suggested that the mean position of the contour lines shifted from the south toward the north from July to September, and then returned to the south during the following fishing season in the study region. We observed that the latitudinal gravity centers of the CPUE in each month varied and were closely related to the mean position of the latitude of the two contour lines.

From 2004–2011, the convergent frontal areas developed in the waters between 40˚–44˚N and 150˚–175˚E, especially in August, and the fishing locations overlapped well with the frontal areas, especially in the waters areas from 40˚ to 44˚N and from 150˚ to 160˚E (Fig.8). It was observed that the CPUEs were noticeably increased along with a close distance between the 17.5℃ SST isotherm and 0.25 mg m^{-3} Chl-*a* isoline.

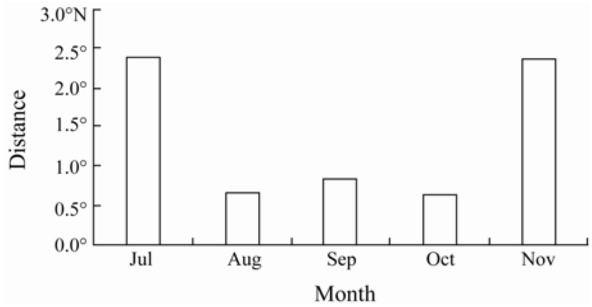

Fig.6 Monthly average distance of the latitudinal mean position between the 17.5℃ SST isotherm and 0.25 mg m^{-3} Chl-*a* isoline from latitude of 150˚ to 175˚E.

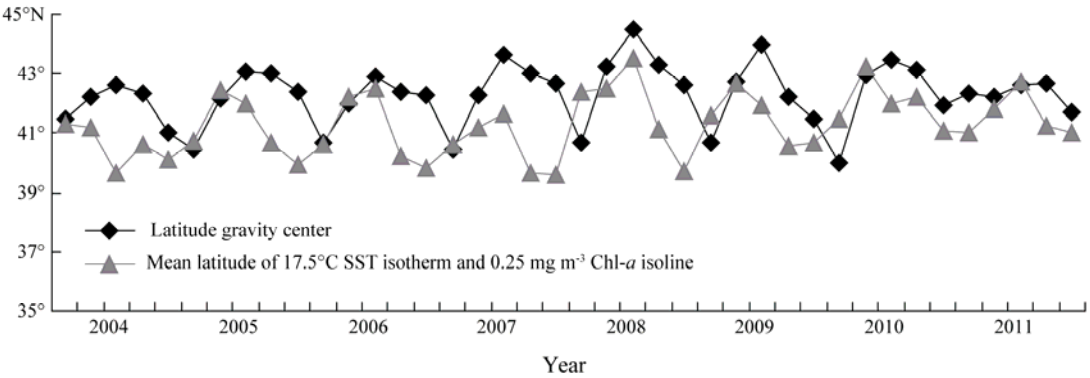

Fig.7 Comparison of the monthly latitudinal gravity centers of the fishing effort with the mean latitude of the 17.5℃ SST isotherm and 0.25 mg m^{-3} Chl-*a* isoline.

4 Discussion

The distribution and the abundance of *O. bartramii* were influenced not only by the water temperature and the availability of the nutrients, but also by other environmental variables, such as sea surface salinity (Chen *et al*., 2010) and sea surface height (Ichii *et al*., 2011). In this study, the SST and Chl-*a* concentration were used to determine the potential productive fishing grounds for *O. bartramii* because of the predominant effects of these environmental factors on the variations of squid stock (Chen *et al*., 2007; Wang *et al*., 2010), and the data of the fishing effort and CPUE were also used in corresponding with these two indicating environmental factors to accurately identify the preferable squid habitats. From the results of the histogram analysis, we found that the suitable SST for the distribution of *O. bartramii* were in the range of 15–19℃ and the Chl-*a* concentration range was 0.1–0.4 mg m^{-3} from July to November over 2004–2011 (Fig.4). The favorable ranges of these environmental factors found in our study were highly consistent with previous findings. For example, Tian *et al*. (2009) estimated a suitability index for *O. bartramii* and determined that the optimal range of the SST was from 16.6 to 19.6℃. Chen and Liu (2006) determined that the monthly suitable SST for the fishing grounds of *O. bartramii* was 14–16℃ in July, 18–19℃ in August, 16–17℃ in September, 15–16℃ in October, and 12–13℃ in November, all of which are in the same range of our findlings. In the case of Chl-*a* concentration, environmental surveys conducted by Shen *et al*. (2004) on the fishing grounds of *O. bartramii* found that the concentration of surface Chl-*a* was between 0.03 and 0.32 mg m^{-3}. It is known that the Chl-*a* concentration is positively related to the abundance of the phytoplankton on the fishing grounds, so the high abundance of the squid is generally occurred in the waters with the Chl-*a* concentration of greater than 0.1 mg m^{-3}.

The oceanic environmental conditions in August tend to significantly affect the annual abundance of squid (Table 1). The increases of the surface temperature or of the Chl-*a* concentration above its fishery-favorable values (15 to 19℃ for the SST and 0.1 to 0.4 mg m^{-3} for the Chl-*a* concentration) individually or together are positively related to the annual *O. bartramii* CPUE with great significance, suggesting that the level of annual squid stock is largely depended on the environmental conditions in August. Additionally, higher correlation coefficient between the numbers of the CPUE and the overlapped favorable areas of the SST and the Chl-*a* concentration might imply that the interaction between water temperature and food availability plays a significant role in the abundance of *O. bartramii*. A well-developed habitat for squid aggregation is an area of warm water with rich nutrients. In October, there is a significant negative correla-

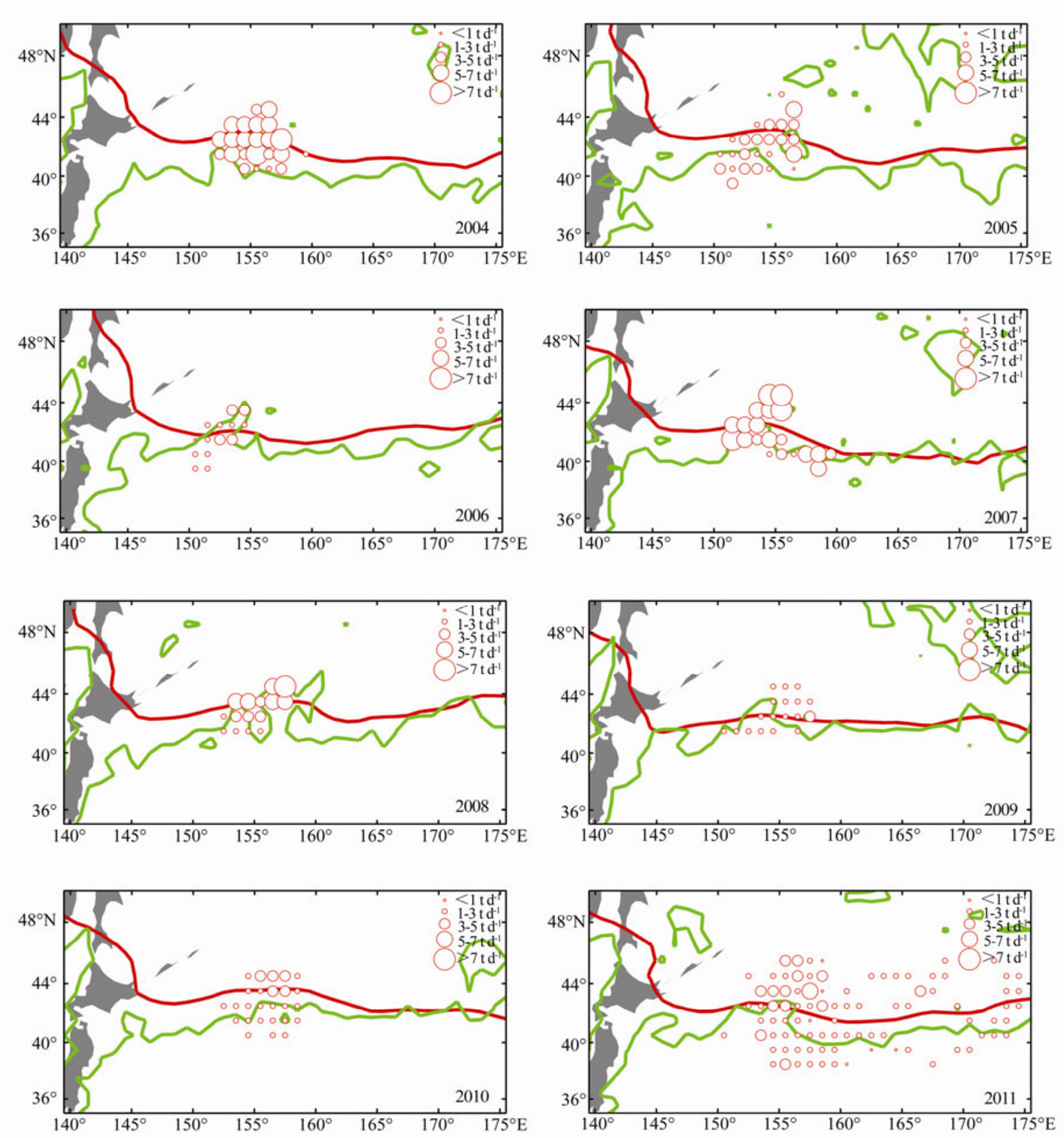

Fig.8 Spatial distribution of the CPUE for *Ommastrephes bartramii* in August superimposed on the optimal contour lines of the 17.5℃ SST isotherm (the red line) and 0.25 mg m^{-3} Chl-*a* isoline (the green line) over 2004–2011.

tion between the CPUE and the Chl-*a* concentration, which might be the reason why some regions with limited nutrients would still lead to the aggregation of the squids with greater abundance.

In this study, the optimal environmental conditions for the *O. bartramii* aggregation were found to be 17.5℃ for the SST and 0.25 mg m^{-3} for the Chl-*a* concentration. During our study, we found that the CPUE at 17.5℃ SST was almost identical to that at 15.5℃ SST, and previous studies also indicated that higher abundance of *O. bartramii* generally corresponded to the warmer SST (Chen *et al*., 2009), so we chose 17.5℃ as the optimal thermal condition. This result is consistent with the conclusion of the study done by Chen (1997) who suggested that 17℃ isotherm was considered to be a good indicator to explore squid fishing grounds.

In this study, we also found a strong connection between the distance of the latitudinal locations of the 17.5℃ SST isotherm and the 0.25 mg m^{-3} Chl-*a* isoline and the abundance of *O. bartramii* from July to November (Fig.5), and the distance between SST and Chl-*a* fronts was positively associated with squid CPUEs. This result indicated that a well formed convergent frontal area would create a suitable ground for the aggregation of *O. bartramii*. Oceanic fronts were defined by their characteristic biological, physical and chemical properties (Belkin *et al*., 2009). The oceanic front of the SST at 17.5℃ brings warmer water to the surroundings, creating an optimal environmental condition for the *O. bartramii* to grow, and the 0.25 mg m^{-3} Chl-*a* front supports the growth of the primary organisms as the food sources that feed the squid (Zainuddin *et al*., 2004). As the concurrent convergence of the two fronts occurred gradually, minor spatial distances could attract large schools of squids, forming one of the most productive habitats of the species. In our first attempt to evaluate the impact of the convergence of oceanographic structure (frontal area) on the abundance of the squid, an optimal combination of the temperature and chlorophyll fronts which could form a potential fishing ground for the western winter-spring squid stock in the Northwest Pacific Ocean was revealed.

From August to October, the distances between the fronts of the two indicating factors tend to be much closer than that of the other fishing months (Fig.6). Such close distance might be the reason why the abundances of the squid in these months are relatively greater. Furthermore, we found that the environmental conditions from August to October appear to be more favorable for the squid aggregation due to the higher SST and more suitable Chl-*a* concentration of the fishing grounds (Fig.3).

The Chinese squid-jigging fishing vessels often follow the seasonal movement of the squid as well as along the fronts of the 17.5℃ SST and of the 0.25 mg m^{-3} Chl-*a* concentration in the Northwest Pacific Ocean (Fig.7). The main fishing locations usually occurred on one side of the SST or Chl-*a* concentration front, or in a close distance between the two (Fig.8). This latitudinal shift of the fishing locations with respect to the frontal areas were the reflection of the migration pattern of *O. bartramii* stock, which was affected by the seasonal changes of the oceanographic features in the TZ (Ichii *et al*., 2009). During the early fishing season (July to September), the squid stock moves northward into a food-rich feeding ground to forage, and later in October or November, once the squids reach sexual maturity, they begin to migrate southward into the subtropical and tropical zones for spawning, which leads to the increased productivity (Murata and Nakamura, 1998). The consistent pattern of the latitude changes between the fishing locations and the fronts suggested that the migration behavior and the abundance of *O. bartramii* are highly sensitive to the spatial and temporal dynamics of the variations of the oceanographic features, particularly the habitats formed by the convergent fronts (Humphries *et al*., 2010). Moreover, it was observed that the CPUEs that were obtained in the waters quite far away from the optimal front were usually very high (Fig.8). In addition to the factors of the SST and Chl-*a* fronts that were considered in this study, other oceanographic features such as eddy fields might also contribute to the high abundance of the squid (Zhang *et al*., 2001; Zainuddin *et al*., 2008).

Environmental conditionals strongly affected the interannual variability of the frontal areas at the large-scale (Tseng *et al*., 2014; Mugo *et al*., 2014). Zainuddin *et al.* (2004) stated that the fronts of the SST and the Chl-*a* concentration were poorly developed in the El Niño event of 1998 comparing to that of the La Niña event of 1999. It was also likely that the Kuroshio and Oyashio Currents have some significant effects on the formation of the SST and Chl-*a* concentration fronts (Sugimoto *et al*., 2001). In our study, the average distances between the two indicating factors from July to November in 2009 and 2010 were 1.38˚ and 1.62˚N, respectively, corresponding to an El Niño and a La Niña event. However, our results can not draw the conclusion that during an El Niño event, the frontal zones are in closer proximity. For example, the average distance of the two fronts in 2007 was 0.92˚N during a La Niña event in the fishing season. More data on the long-term fishery and environmental conditions were needed in order to further analyze the relationship between the large-scale climate changes and the locations of the fronts.

Overall, this study provides a new insight on exploring the influence of the convergent oceanographic features (frontal area) on the abundance and distribution of the western stock of the winter-spring cohort of *O. bartramii* in the Northwest Pacific Ocean over the years of 2004–2011. We evaluated the favorable SST and Chl-*a* concentration ranges for the squid aggregation, of which the SST at 17.5℃ and the Chl-*a* concentration at 0.25 mg m^{-3} were considered to be the optimal environmental indicators to locate the most productive fishing grounds for *O. bartramii*. These findings suggest that the annual squid abundance predominately depends on the fishery-favorable environmental conditions in August. Minor spatial difference between the SST and Chl-*a* fronts was also positively associated with the squid abundance. Furthermore, the latitudinal gravity centers of CPUE is varied and closely related to the mean latitudinal position of the contour lines of the SST and the Chl-*a* concentration. The results and findings of this study will be useful in understanding the response of the squid to the convergent frontal areas and in improving our ability to explore the highest productive fishing grounds of *O. bartramii*.

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