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Impacts of climatic and marine environmental variations on the spatial distribution of *Ommastrephes bartramii* in the Northwest Pacific Ocean

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Abstract

Ommastrephes bartramii is an ecologically dependent species and has great commercial values among the Asia-Pacific countries. This squid widely inhabits the North Pacific, one of the most dynamic marine environments in the world, subjecting to multi-scale climatic events such as the Pacific Decadal Oscillation (PDO). Commercial fishery data from the Chinese squid-jigging fleets during 1995–2011 are used to evaluate the influences of climatic and oceanic environmental variations on the spatial distribution of *O. bartramii*. Significant interannual and seasonal variability are observed in the longitudinal and latitudinal gravity centers (LONG and LATG) of fishing ground of *O. bartramii*. The LATG mainly occurred in the waters with the suitable ranges of environmental variables estimated by the generalized additive model. The apparent north-south spatial shift in the annual LATG appeares to be associated with the PDO phenomenon and is closely related to the sea surface temperature (SST) and sea surface height (SSH) on the fishing ground, whereas the mixed layer depth (MLD) might contribute limited impacts to the distribution pattern of *O. bartramii*. The warm PDO regimes tend to yield cold SST and low SSH, resulting in a southward shift of LATG, while the cold PDO phases provid warm SST and elevated SSH, resulting in a northward shift of LATG. A regression model is developed to help understand and predict the fishing ground distributions of *O. bartramii* and improve the fishery management.

Key words: *Ommastrephes bartramii*, fishing ground gravitational centers, climate change, oceanographic variables, Northwest Pacific Ocean

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1 Introduction

The neon flying squid, *Ommastrephes bartramii*, is a highly migratory oceanic species widely distributed throughout subtropical to temperate waters of the world's ocean (Murata, 1990; Chen et al., 2009). High abundance of *O. bartramii* occur in the regions between 20°N and 50°N in the North Pacific Ocean (Fig. 1; Roper et al., 1984), which support important commercial squid fisheries for many countries such as Japan, South Korea and China (Bower and Ichii, 2005; Chen et al., 2008). Based on the analysis of parasite fauna (Bower and Margolis, 1991) and mantle length frequency data (Murakami et al., 1981; Murata, 1990), the North Pacific population of *O. bartramii* is divided into two putative seasonal cohorts (Bower and Ichii, 2005): an autumn cohort including a central and an eastern stock (Chen and Chiu, 2003), and a winter-spring cohort with a western and a central-eastern stock (Murata and Hayase, 1993). Both cohorts have a 1-year lifespan (Yatsu et al., 1997, 1998). During 1995–2011, the Chinese squid-jigging fleets mainly targeted the western stock of winter-spring cohort on the fishing ground between 35°–50°N and 150°–175°E from July to November, with annual catches ranging from 36 764 t to 132 000 t.

As ecological opportunists, the short lifespan history for ommastrephid squid determines high susceptibility of fishing ground distributions to variations in the environmental conditions (Cao et al., 2010). Adult squid tend to move rapidly in response to changes in the biotic and abiotic environments on the fishing ground (Humston et al., 2000). Previous studies have indicated that many oceanographic variables play critical influences on the preference of *O. bartramii* for particular habitat and its distribution of fishing ground. For example, variability in sea

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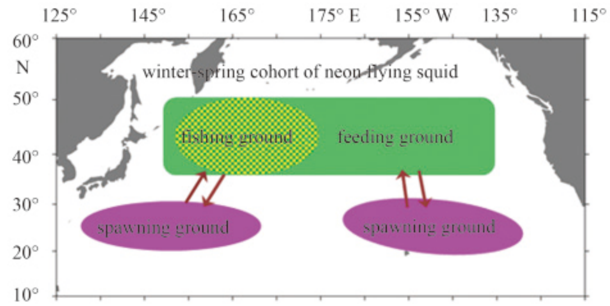

Fig. 1. The migration pattern of the winter-spring cohort of neon flying squid *Ommastrephes bartramii*, showing the distribution of the spawning and feeding grounds in the North Pacific. The yellow area is the study area corresponding to the fishing ground for the Chinese squid-jigging fleets in this paper.

surface temperature (SST) could greatly affect the distribution of *O. bartramii*, productive squid abundance tended to occur in the areas with high SST variability near Hokkaido during 1995–2001 (Wang et al., 2010). The squid stocks are likely to aggregate in the waters with high SST anomaly (SSTA). In general, the occurrence of low SSTA on the fishing ground coincided with sparse squid distribution (Yu et al., 2013). Additionally, sea surface height (SSH) was considered to be an important indicator closely related to the distributions of fishing ground. Chen et al. (2010b) suggested the SSH anomaly (SSHA) could be used as a proxy from the available environmental conditions to identify the potential fishing ground and optimal habitats of *O. bartramii*, the optimal range of SSHA varied with fishing seasons, but the values were generally below zero.

Large-scale climatological and environmental variability, such as Pacific Decadal Oscillation (PDO), El Niño-Southern Oscillation (ENSO) and the Kuroshio-Oyashio Current interactions, may lead to fluctuations in the surrounding oceanographic environment on the fishing ground and consequently result in large uncertainties of spatial distribution patterns of squid species (Anderson and Rodhouse, 2001). For example, Xu et al. (2012) suggested that the spatial shifting in the jumbo flying squid (*Dosidicus gigas*) population was significantly related to ENSO events off Peruvian waters. In the La Niña years, the average SST suffered from a dramatic decline and the main fishing ground tended to move northward for 1°–2° latitude compared with that in the years of El Niño. Variations in the distribution of the western stock of winter-spring cohort of *O. bartramii* also proved to be associated with ENSO phenomenon. ENSO events strongly affected squid distribution on the feeding ground, resulting in a southward shift of the fishing grounds in El Niño years and a northward shift in La Niña years, respectively (Chen et al., 2007). Moreover, Chen et al. (2012a) evaluated the impacts of the path and transport of the Kuroshio Current on the spatial distribution of *O. bartramii* combined with the PDO phenomenon. Their findings suggested that the Kuroshio strength seemed to structure the patterns of variations in the north-south movement of *O. bartramii*. From the research above-mentioned, we could draw a conclusion that the *O. bartramii* actively reacted to variability in regional oceanographic conditions on the fishing ground and large-scale climatic fluctuations in the North Pacific, shifting its spatial distribution into more suitable habitat. However, information was unavailable with respect to the long-term influences of PDO events combined with various environmental variables on the distributions of *O. bartramii*, the understanding of the relationship between the environmental conditions and variability in gravity centers of fishing ground for *O. bartramii* was limited and unclear so far.

In the present study, we examined the relationship between temporal variations in the PDO events and interannual variability in spatial distribution of western stock of winter-spring cohort of *O. bartramii* during July to November over the period from 1995 to 2011, and evaluated how the anomalies of SST, SSH and mixed layer depth (MLD) on the fishing ground led to the annual changes of squid spatial distribution and migration. Linear regression analyses of latitudinal gravity centers of squid abundance versus PDO index would be used to develop a fishery forecasting model for predicting the squid spatial distribution. Such a study can help explore the underlying process how the squid responds to the multi-scale oceanographic variability and develop a capacity of understanding and forecasting the dynamics of squid populations for better fishery management.

2 Materials and methods

2.1 *Fishery data*

In this study, we chose the fishing ground between 35°–50°N and 150°–175°E in the Northwest Pacific Ocean as our study area (Fig. 1). The total annual catch of *O. bartramii* by the Chinese squid-jigging fleets in this region accounted for more than 80% of the total catch (Chen et al., 2007). Commercial fishery data on daily catch (t), fishing effort (days fished), fishing dates and locations (longitude, latitude), at the resolution of 1° latitude by 1° longitude, were obtained from the Chinese Squid-jigging Technology Group of Shanghai Ocean University from July to November during 1995–2011.

Catch per unit effort (CPUE) was suggested to be a good indicator of squid stock abundance on the fishing ground (Chen et al., 2008; Cao et al., 2009). There were various methods to calculate the monthly nominal CPUE (Tian and Chen, 2010). In this study, a spatial scale of 1°×1° was defined as a fishing unit, and the nominal CPUE within a fishing unit was calculated by the following equation:

$$\mathrm{CPUE}_{ymij} = \frac{\sum \mathrm{catch}_{ymij}}{\sum \mathrm{times}_{ymij}}, \tag{1}$$

whereCPUE_{ymij}, $\sum\mathrm{catch}_{ymij}$ and $\sum\mathrm{times}_{ymij}$ are the monthly nominal CPUEs, the sum of catches for all the fishing fleets within a fishing grid and the sum of all fishing efforts of all fishing fleets within a fishing grid, respectively, at longitude *i*, latitude *j* in month *m*, year *y*.

For the purpose of better understanding the spatial distribution of fishing ground of *O. bartramii*, the longitudinal and latitudinal gravitational centers (LONG and LATG) of nominal CPUE in month *m* were estimated by:

$$\mathrm{LONG}_m = \frac{\sum_{i=1}^{K}(\mathrm{LONG}_i \times \mathrm{CPUE}_{mi})}{\sum_{i=1}^{K}\mathrm{CPUE}_{mi}}, \tag{2}$$

$$\mathrm{LATG}_m = \frac{\sum_{i=1}^{K}(\mathrm{LATG}_i \times \mathrm{CPUE}_{mi})}{\sum_{i=1}^{K}\mathrm{CPUE}_{mi}}, \tag{3}$$

where LONG_i is the longitudinal mid-point of the *i*th area of 25 longitude widths between 150°E and 175°E; $LATG_i$ is the latitudinal mid-point of the ith area of 15 latitude widths between 35°N and 50°N; $CPUE_{mi}$ is the nominal CPUE in area i in month m; K is the number of total fishing units.

2.2 *Climatic index and environmental data*

The PDO index (PDOI) was essentially utilized to describe predominant climatic oscillation in the Pacific Ocean. The PDOI was defined as the time series of leading principal component through an Empirical Orthogonal Function (EOF) analysis of SST anomalies northward of 20°N during the periods 1900–1993 in the North Pacific (Zhang et al., 1997). The monthly PDOI data from 1995 to 2011 were obtained from Joint Institute for the Study of the Atmosphere and Ocean (http://jisao.washington.edu/pdo/PDO.latest). Positive and negative PDOI represented the warm and cold PDO regimes, respectively. During a warm PDO phase, anomalous cool surface waters tended to occur in the western and central North Pacific Ocean, the eastern Pacific Ocean and the west coast of the Americas became warm; during a cold PDO phase, the opposite pattern occurred (Mantua and Hare, 2002).

The oceanographic variables considered in this study included SST, SSH and MLD on the fishing ground of *O. bartramii*, which appeared to be affected by the large-scale climatic variations. The monthly environmental data from July to November during 1995–2011 were sourced as follows: (a) SST and SSTA from the NOAA High-resolution Blended Analysis (http://apdrc.soest.hawaii.edu/data); (b) SSH and SSHA from Live Access Server of National Oceanic and Atmospheric Administration OceanWatch (http://oceanwatch.pifsc.noaa.gov/las/servlets/dataset; (c) MLD and MLD anomaly (MLDA) from the National Centers for Environmental Prediction (http://apdrc.soest.hawaii.edu/las/v6/dataset). All the environmental data were grouped by the 1°×1° grid for each month to correspond to the spatial resolution of the fishery data.

The PDO events played significant influences on the oceanographic features on the fishing ground of ommastrephid squid (Yu et al., 2015). To evaluate the impacts of climatological variability on the oceanographic factors including SST, SSH and MLD, time series contour maps of oceanographic conditions in the sections of the average longitudinal and latitudinal gravitational centers from July to November over 1995–2011 were created using the monthly 1°×1° environmental data. Linear regression analysis was further conducted to establish a forecast model for predicting the gravity centers of squid fishing ground, the annual average PDOI was used as an independent variable in the linear model.

2.3 *Generalized additive model*

The generalized additive model (GAM) was commonly applied to deal with non-linear relationships between the response variable and explanatory variables, which was an extension of generalized linear model (GLM) (Guisan et al., 2002). We explored the environmental preference of *O. bartramii* for particular habitats and the impacts of oceanographic variables on the squid abundance by the equation of the GAM as follows:

$$\ln(\mathrm{CPUE}) = \alpha + \sum_{i=1}^{p} f(x_i) + \varepsilon\,, \tag{4}$$

where CPUE is the nominal CPUE for each fishing unit; α is the intercept term of the model; f is the non-parametric, smooth function (spline smoother) specifying the effects of environmental variables; x_i is the ith explanatory variable; ε is the residual error, $\varepsilon=\sigma^2$ and $E(\varepsilon)=0$.

3 Results

3.1 *LONG and LATG of O. bartramii in relation to PDO*

During 1995–2011, the gravity centers of fishing ground for *O. bartramii* mainly concentrated in the regions between 37°–45°N and 150°–170°E (Fig. 2). However, the spatial patterns exhibited obvious seasonal variability. In July, the fishing ground gravity centers were dispersive along the longitudinal direction, but were

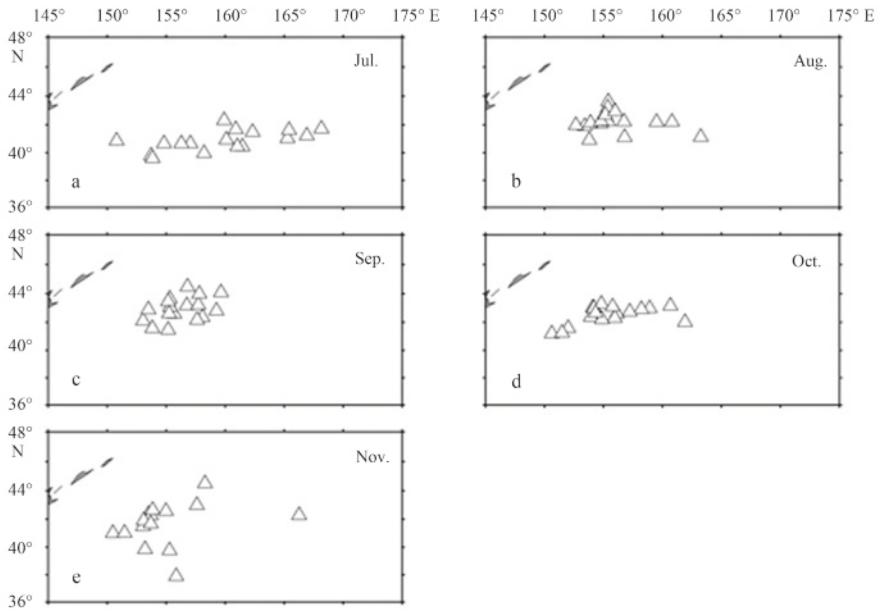

Fig. 2. The annual distribution of fishing ground gravity centers of *Ommastrephes bartramii* from July to November during 1995–2011.

confined within a narrow latitudinal band. Fishing grounds were generally located in the waters between 39°–43°N and 150°–167°E (Fig. 2a). In August, the fishing grounds shifted northwestward, mainly aggregated in the areas between 40°–44°N and 153°–157°E, with few fishing locations distributed from 160°E to 165°E (Fig. 2b). The fishing grounds became more concentrated in September, forming an oblique ellipse-shape area bounded by 41°–45°N and 153°–160°E (Fig. 2c). Later in October, the fishing grounds started to shift eastward (Fig. 2d), and expanded into the waters between 37°–45°N and 150°–170°E in November (Fig. 2e).

From the patterns of alternating positive and negative PDOI, two full warm and cold PDO cycles occurred in the North Pacific over the periods 1995–2011 (Fig. 3). The annual average LATG of squid was located in the waters between 40°N and 43.5°N. From 1995 to 2000 the LATG shifted northward, then deviated southward during 2000–2001. From 2002 to 2011, the average LATG ranged from 41.5°N to 43°N and gradually moved northward. Warm and cold PDO phases tended to result in a southward and northward shift of LATG, respectively (Fig. 3a). The annual average LONG over the periods 1995–2011 fluctuated with the values varied between 153°E and 161°E, deviating westernmost in 1996 and easternmost in 2000 (Fig. 3b). Correlation analyses suggested that the PDOI was significantly negatively related to the LATG of *O. bartramii* (r=–0.679, P<0.01) but was not significant correlated with the LONG (r=–0.275, P=0.142>0.05). However, it was notable that the variability of LONG presented positive and negative relationships with the PDOI during warm and cold PDO phases, respectively (Fig. 3b).

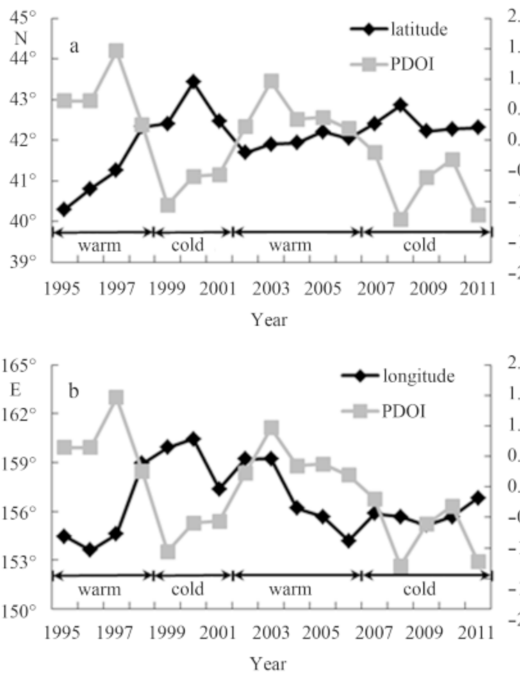

Fig. 3. Annual average (a) latitudinal gravity centers (LATG), and (b) longitudinal gravity centers (LONG) of *Ommastrephes bartramii* in relation to the Pacific Decadal Oscillation index (PDOI).

Correlation analyses revealed that the PDO played a critical role in regulating the latitudinal distributions of *O. bartramii*. Therefore, the annual average PDOI was employed as an independent variable in the linear regression model to predict the squid distribution. The resultant empirical model was significant (P<0.05), suggesting that LATG was negatively and significantly correlated with the PDO (Table 1). The forecast model was established as follows:

$$\mathrm{LATG} = 42.019 - 0.638 \times \mathrm{PDOI}, \tag{5}$$

where LATG (°N) was latitudinal gravitational centers of *O. bartramii*; PDOI was the annual average PDO index.

Table 1. Regression model between the latitudinal distribution of *Ommastrephes bartramii* and the Pacific Decadal Oscillation index (PDOI)

Model	95% *CI*	*P*
LATG=α_0+α_1×PDOI		
α_0=42.019	41.732 to 42.307	<0.001
α_1=–0.638	–1.017 to –0.259	0.003
r=0.679, F=12.855, P=0.003		

Notes: LATG represents latitudinal gravity centers, *CI* confidence interval, and *r* correlation coefficient.

3.2 *Time-latitude and time-longitude sections of the oceanographic conditions*

The average LATG (42.5°N) and LONG (156.5°E) during 1995–2011 were selected to be the sections creating the time series contour maps. Interannual variability was shown in the oceanographic conditions in the sections of latitude and longitude within the study periods (Fig. 4). Isopleths of time-latitude section of oceanographic variables showed that SSTA became higher in the area between 36°N and 45°N from 1998 to 2000, 2008 and from 2010 to 2011. Obvious cold water occurred on the fishing ground of *O. bartramii* in the year 1995–1997, 2001–2002 and 2006 (Fig. 4a). The SSHA was elevated up to 40 cm in the area of 39°N south and decreased lower than 0 cm in the area of 44°N north during 1995–2011. In these two areas no significant variability was observed. While the SSHA in the waters between 39°N and 44°N fluctuated and approximately ranged from 0 cm to 20 cm, elevated SSHA was observed in 1998–2000, 2005 and 2010–2011 (Fig. 4b). However, MLDA in most areas was between –10 m and 10 m, there was no significant interannual variation in the MLDA (Fig. 4c). In the longitude section, the results suggested that warm temperature waters occupied the waters on the fishing ground in the years 1998–2000, 2005, 2008 and 2010–2011, but showed differences in the location (Fig. 4d). On the fishing ground between 150°E and 170°E, significant elevated SSHA was observed in the year 1997–2003, 2004–2005 and 2010 between 153°E and 157°E (Fig. 4e). For the MLDA, the MLDA deepened evidently in 2002 and 2009 (Fig. 4f).

3.3 *GAM results*

The GAM plots showed the best fitting smoothers for the effects of the oceanographic conditions on the squid abundance (Fig. 5). Significant relationship was identified between the CPUE and the environmental variables considered in this study (P<0.01) except MLDA. The CPUE of squid appeared to slightly increase with the SSTA, the preferred range of SSTA tended to be between –2°C and 2°C (Fig. 5a). With respect to the SSHA, a significantly negative correlation was examined between the squid abundance and the SSHA, lower SSHA was possibly favorable for the squid aggregation, the preferred SSHA tended to be between

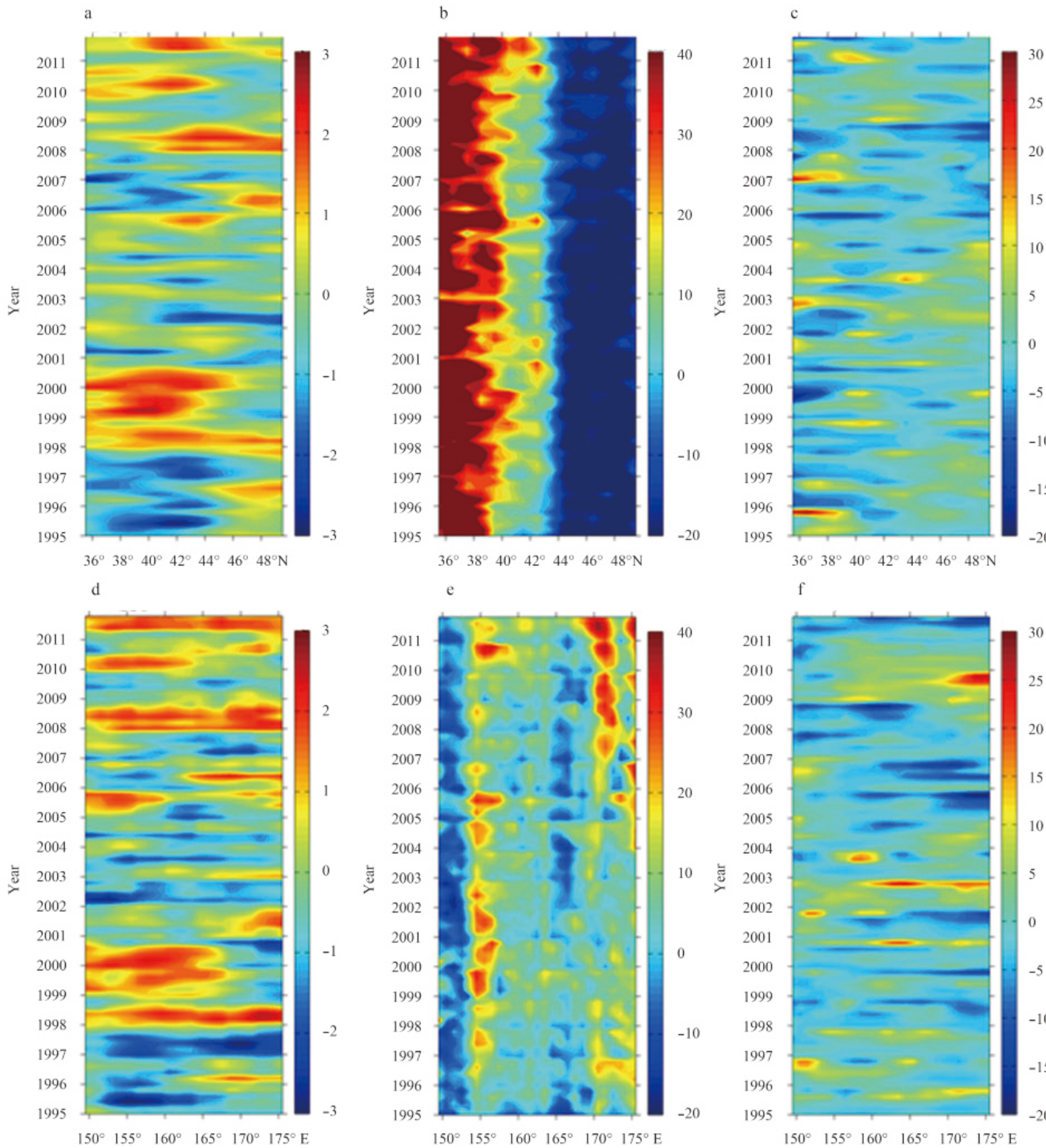

Fig. 4. Time-latitude section of monthly anomalies of sea surface temperature (SST, °C) (a), sea surface height (SSH, cm) (b), mixed layer depth (MLD, m) (c), and time-longitude section of monthly anomalies of SST (°C) (d), SSH (cm) (e), MLD (m) (f) in the Northwest Pacific Ocean during 1995–2011.

–20 cm and 30 cm (Fig. 5b). For MLDA, fishing grounds with a high frequency aggregation of squid occurred in the waters with MLDA varied from –10 m to 10 m (Fig. 5c).

3.4 *Interannual variability in the environmental conditions*

During 1995–2011, the average SSTA and SSHA from July to November on the fishing ground of *O. bartramii* ranged from –1.0°C to 1.0°C and from –3.6 cm to 6.1 cm. Warm PDO phases tended to yield low SSTA and SSHA, whereas cold PDO phases appeared to result in high SSTA and SSHA, aside from few particular years (Figs 6a and b). The MLDA subjected to large fluctuations over 1995–2011, it ranged from –3.6 m in 2005 to 4.3 m in 2002. However, the variability of MLDA did not well coincide with the PDO phases (Fig. 6c). Of the regression analysis, both the SSTA and SSHA on the fishing ground were positively correlated to the LATG and negatively correlated to the PDOI, but no significant relationships were found between the MLDA and squid distribution (LONG and LATG), as well as the PDOI (Table 2).

4 Discussion

4.1 *Spatio-temporal distributions of O. bartramii*

Research was considerably limited on the long-term spatio-temporal variability in the squid distribution for the western

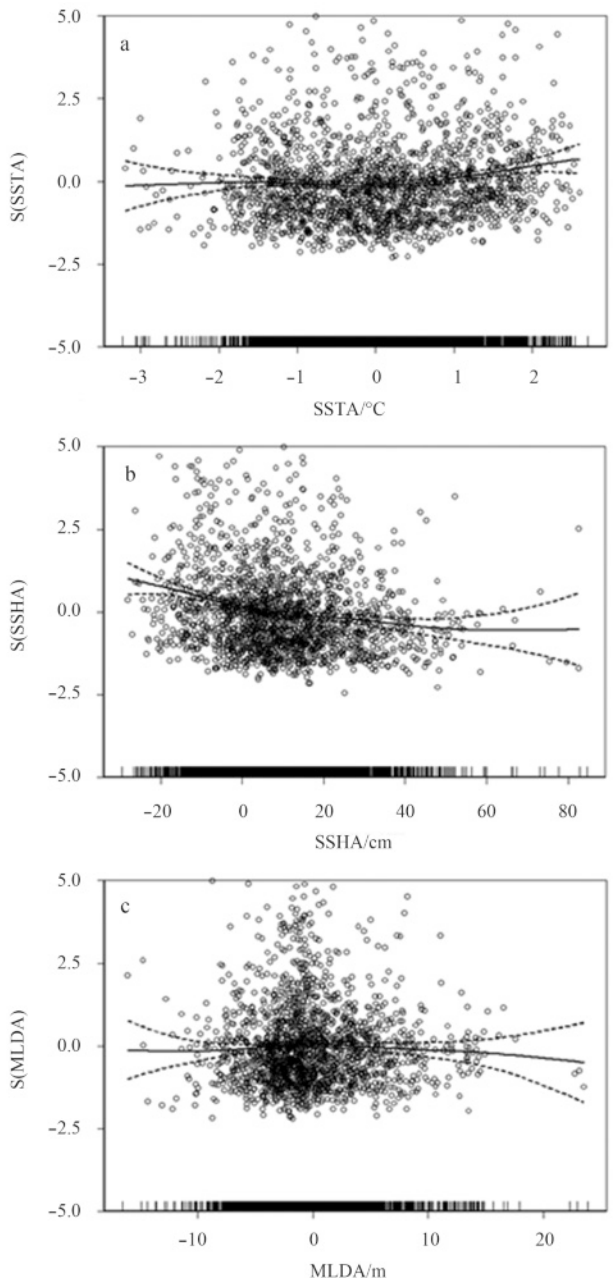

Fig. 5. GAM-estimated the preference of sea surface temperature anomaly (SSTA) (a), sea surface height anomaly (SSHA) (b) and mixed layer depth anomaly (MLDA) (c) for the fishing ground distributions of *Ommastrephes bartramii* in the Northwest Pacific Ocean from 1995 to 2011.

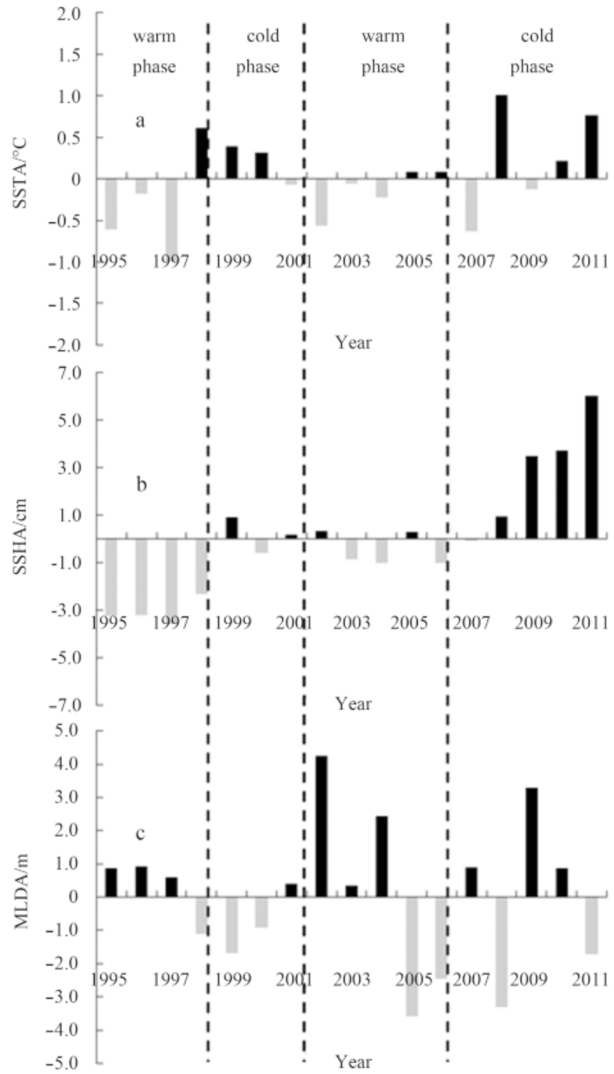

Fig. 6. Annual average sea surface temperature anomaly (SSTA) (a), sea surface height anomaly (SSHA) (b) and mixed layer depth anomaly (MLDA) (c) from July to November on the fishing ground from 1995 to 2011.

Table 2. Correlations between the environmental variables (sea surface temperature anomaly, SSTA; sea surface height anomaly, SSHA; mixed layer depth anomaly, MLDA) on the fishing ground and the gravity centers of fishing ground and the Pacific Decadal Oscillation index (PDOI), respectively

Environmental variables	LATG		LONG		PDOI	
	r	*P*	*r*	*P*	*r*	*P*
SSTA	0.621	0.004	0.308	0.115	–0.710	0.001
SSHA	0.505	0.019	0.139	0.297	–0.738	<0.001
MLDA	–0.374	0.070	–0.006	0.490	0.296	0.124

Notes: LATG represents latitudinal gravity centers and LONG longitudinal gravity centers

stock of winter-spring cohort of *O. bartramii*. In this study, there were clear indications of seasonal and interannual variability in the preferred latitude and longitude during 1995–2011(Figs 2 and 3). From the analyses on the LATG and LONG of squid, the monthly LATG was mainly distributed in the areas between 39°N and 44°N, undertaking north-south movement from July to November. The reason caused this shift in the LATG might be due to the life history characteristic of *O. bartramii*, migrating northward for feeding from June to August and returned southward for spawning during October-November (Fan et al., 2009). Additionally, the annual average LATG dramatically increased over 1995–2000 and slightly fluctuated in the later ten years. With regard to the LONG, the squid was highly concentrated in the preferred longitude in August and September, but in other fishing seasons, the fishing grounds were widely distributed along the longitudinal direction between 150°E and 170°E. During 1998–2003, the fishing ground gravity centers were distributed in the east of 156°E. These conclusions as mentioned above were basically consistent with previous studies. For example, Chen et al. (2003) suggested the distribution of fishing ground of *O. bartramii* was mainly located in the waters between 153°E and 161°E from 1995 to 2001. Later, according to the Chinese squid-jigging fisheries data over 1998–2007, Chen et al. (2010a) demonstrated that the monthly favorable fishing ground was distributed between 157°–169°E and 40°–42°N in July, 151°–158°E and 41°–44°N in August, 152°–160°E and 42°–45°N in September, 151°–160°E and 42°–44°N in October, 150°–156°E and 40°–42°N in November, respectively.

4.2 *Influences of large-scale climatic conditions*

Interannual variability in the spatial distribution of pelagic species tended to be affected by ecological processes in marine ecosystems, which was environmentally driven by the large-scale climatic conditions (Stenseth et al., 2004; Tian et al., 2008). Variability in the distribution of yellowfin tuna *Thunnus albacares* had been proved to be closely linked to the Indian Ocean Dipole (IOD). Catch distributions were confined to the northern and western margins of the western Indian Ocean during positive IOD events; when the regime shifted to the negative IOD events, fishing grounds expanded into the central waters of the western Indian Ocean (Lan et al.,). Tian et al. (2011) suggested 2004 that the latitudinal distribution of four stocks of spear squid *Loligo bleekeri* in the Japan Sea and the coastal waters of the Pacific was largely depended on the climate regime shift associated with PDO, ENSO, Arctic Oscillation (AO) and monsoon. For the western winter-spring cohort of *O. bartramii*, results suggested that the regime shift of PDO might change the marine environment conditions on the fishing ground and lead to the interannual variability in the squid latitudinal distributions. Warm PDO regimes tended to yield cold SSTA and low SSHA on the fishing ground in the Northwest Pacific, resulting in a southward shift of LATG. While cold PDO phases provided warm SSTA and high SSHA, resulting in a northward shift of LATG. The negative relationship between the PDOI and the LATG was consistent with the results from Chen et al. (2012a), however, their studies mainly focused on the impacts of the Kuroshio Current on the latitudinal distribution of fishing ground. Our studies explored the potential process that the PDO events affected the oceanographic conditions on the fishing ground and further influenced the squid distribution.

4.3 *Impacts of oceanographic conditions on the fishing ground*

Extensive studies has been conducted to evaluate the impacts of oceanographic variables, including SST and SSH, but few on MLD, on the spatial distribution of *O. bartramii* on the fishing ground. Fan et al. (2004) suggested that the favorable SST for the winter-spring cohort of *O. bartramii* was between 10°C and 22°C with optimal SST varying from 15°C to 17°C. Tian et al. (2009) developed a habitat suitable index (HSI) model to evaluate the habitat of *O. bartramii*, they defined the optimal habitat for *O. bartramii* with SST from 16.6°C to 19.6°C and SSH from –20 cm to –4 cm. However, their conclusions were inclined to emphasize the optimal ranges of oceanographic features that the squid preferred to inhabit. In this study, highlights were focused on the influences of variations in SSTA, SSHA and MLDA on the spatial distribution of *O. bartramii*. The GAM model was used to evaluate the preferred ranges of the three oceanographic variables for squid. Results showed the squid was likely to occur in the waters with SSTA ranging from –2°C to 2°C, SSHA ranging from –20 cm to 30 cm and MLDA ranging from –10 m to 10 m, respectively (Fig. 5). Furthermore, higher SSTA and SSHA tended to result in a northward movement of squid (Table 2). From the contour maps, it was evidently observed that annual LATG shifted to the estimated preferred ranges of oceanographic variables based on the GAM method, especially from the SSTA contour map. The surface water became much warmer in the northern regions of fishing ground between 40°N and 45°N in 1998–2000, 2005, 2008 and 2010–2011 (Fig. 4a), the LATG then moved northward in these years (Fig. 3a). The SSHA on the fishing ground was found to be located in the optimal range estimated by the GAM model. Higher SSHA was clearly observed during 1998–2000, 2005 and 2010–2011 associated with a northward shift of the LATG (Fig. 4b).

No significant correlation is identified between the squid distribution and the variation in the MLDA in our study, suggesting that the impacts of MLD on the fishing ground distributions are unclear. However, the role of MLD is important in controlling the vertical stratification on the fishing ground and should be taken into account in the analysis. Climate change appeares to alter the MLD and results in fluctuations in the productivity over a range of trophic levels, which possibly induce the changes of marine fish abundance and distribution (Polovina et al., 1994). Su et al. (2011) examined the interannual variability in the distribution of blue marlin *Makaira nigricans* in the North Pacific, spatial pattern of this species was apparently related to shifts in SST and the deepening of MLD. Chang et al. (2013) suggested the spatial shifts in optimal habitats of swordfish *Xiphias gladius* in the northwest area of the equatorial Atlantic Ocean might be related to the reduced MLD and elevation in SSH in 2005. During 1995–2011, most regions on the fishing ground of *O. bartramii* were occupied by the waters with the MLDA from –10 m to 10 m, which was within the preferred range. Therefore, the MLDA had limited influences on the squid distribution. Annual average MLD from July to November on the fishing ground of *O. bartramii* was less than 30 m, adult squid experienced vertical migration, they occupied in deeper water. Hence, not only the MLD but also vertical temperature in deep water was needed to be considered in the future research, especially the water temperature structure between 0–50 m (Chen et al., 2012b).

In summary, significant interannual and seasonal variability in the LATG and LONG are exhibited for the western stock of winter-spring cohort of *O. bartramii* during 1995–2011. The LATG performs north-south movement during July to November and mainly occupy the waters with the preferred ranges of environmental variables estimated by the GAM model. Shifts of the LATG are closely linked to the large-scale climatic events (e.g., PDO) and regional oceanographic conditions (e.g., SSTA and SSHA). However, the mixed layer depth (MLD) may contribute limited impacts to the spatial pattern of *O. bartramii*. Warm PDO regimes tended to yield cold SSTA and low SSHA, resulting in a southward shift of LATG, while cold PDO phases provids warm SSTA and high SSHA, resulting in a northward shift of LATG. Furthermore, a LATG forecast model is developed to predict the dynamics of spatial distribution of fishing ground of *O. bartramii*. These findings provided preliminary insights into the large- and local-scale environmental conditions affecting the fishing ground distributions of *O. bartramii* in the Northwest Pacific Ocean.

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