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The effect of sea surface temperature increase on the potential habitat of *Ommastrephes bartramii* in the Northwest Pacific Ocean

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Abstract

In the Northwest Pacific Ocean, the squid jigging fisheries from China, Japan and other countries and regions have targeted the west winter-spring cohort of neon flying squid (*Ommastrephes bartramii*) from August to November since the 1970s. This squid is a short-lived ecological opportunist with a life-span of about one year, and its population is labile and recruitment variability is driven by the environment or climate change. This variability provides a challenge for ones to forecast the key habitats affected by climate change. The catch data of *O. bartramii* from Chinese squid jigging fishery and the satellite-derived sea surface temperature (SST) data are used in the Northwest Pacific Ocean from August to November of 1998 to 2004, the SST preferences of *O. bartramii* corresponding to high values of catch per fishing day (CPUE) are determined and monthly potential habitats are predicted using a histogram analysis of the SST data. The possible changes in the potential habitats of *O. bartramii* in the Northwest Pacific Ocean are estimated under four climate change scenarios based on the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change, i.e., 0.5, 1, 2 and 4°C increases in the SST because of the climate change. The results reveal an obvious poleward shift of the potential habitats of *O. bartramii* in the Northwest Pacific Ocean.

Key words: *Ommastrephes bartramii*, sea surface temperature increase, potential habitat, Northwest Pacific Ocean

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1 Introduction

Ommastrephes bartramii is a short-lived ecological opportunist which generally have a life-span of about one year (Anderson and Rodhouse, 2001). Its official common name is the "red flying squid" (Turgeon et al., 1998), but it is frequently referred to in the literature as the "neon flying squid" (Bower and Ichii, 2005). It is a large oceanic squid distributed in temperate and subtropical waters of the Pacific, Indian and Atlantic Oceans (Murata, 1990; Agnew, 2002). The north Pacific population occurs mainly between 20°N and 50°N and consists of two cohorts: a fall cohort and a winter-spring cohort (Yatsu et al., 1998, 2000). The distribution of the fall-cohort stock is mostly distributed in the east of 170°E. The winter-spring cohort is widely distributed across the north Pacific, but is mainly distributed in the west of 170°E with most of this cohort occurring in the west of 165°E (Bower and Ichii, 2005). Since 1993, the western winter-spring cohort has been mainly fished by the squid jigging fleets from China, other countries and regions (Chen et al., 2007).

O. bartramii makes an annual round-trip migration between its subtropical spawning grounds and its northern feeding grounds near the subarctic boundary (Murata and Nakamura, 1998). As a result of seasonal changes at latitudes of the SST, the spawning grounds shift from near 29°–34°N for the fall cohort to near 21°–30°N for the winter-spring cohort (Yatsu et al., 1998). The vertical distribution of *O. bartramii* changes with a growth and varies geographically. Near the subarctic frontal zone (42°–46°N), the adult squid inhabit 0–40 m depths during the night and 150–350 m depths during the day (Nakamura, 1993, 1994a, b, 1995a, b; Murata and Nakamura, 1998; Tanaka, 1999). In more oligotrophic southern waters (26°–28°N), they occur at 0–100 m depths during the night and below 400 m depth during the day (Nakamura, 1993, 1995b).

O. bartramii is an opportunist and short-lived species, with a single year class. Previous studies show that biographical environments play an important role in regulating the distribution and abundance of *O. bartramii* (Yatsu et al., 1998; Wang and Chen, 2005; Chen et al., 2007). The distribution, abundance and life history of *O. bratramii* were found to be related to surface oceano-

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graphic variability (Ichii et al., 2006), the Kuroshio Current (Cao et al., 2009), and El Niño/La Niña events (Chen et al., 2012; Sánchez-Velaso et al., 2000). Many studies show that the SST strongly influences the spatio-temporal distribution of fishing grounds and habitat (Roberts, 1998; Waluda et al., 1999, 2006; Rodhouse, 2001; Bower and Ichii, 2005; Ichii et al., 2006; Shao and Zhang, 2006). The distribution and abundance of *O. bartramii* in the central waters of North Pacific are strongly affected by water temperature and salinity, with the water temperature having a higher predictive power for estimating abundance (Chen and Chiu, 1999).

A habitat is a geographic and ecological environment that provides a direct support for fish populations and communities (Bower and Ichii, 2005; Tseng et al., 2011). Individual fish (squid) habitat requirements shift with an ontogeny. When the habitat shrinks or disappears, the fish abundance can be reduced or lead to extinction (Murata, 1990). Therefore, it is important to understand dynamics of the fish habitat, which may explain the effect of environmental variables on the distribution and abundance of fish populations.

The SST was determined to be one of the most important variables or the single most important variable to predict the location of the optimal habitat of squid (Chen and Chiu, 1999; Zhang et al., 2004; Chen et al., 2007). Therefore, it could be reasonably assumed that the SST was the dominant variable in determining the squid habitat and subsequent production. In the present study, the fishery data of *O. bartramii* and the SST derived from a satellite to identify the favorable SST range of *O. bartramii* in the Northwest Pacific Ocean was used to predict potential impacts of the climate change on *O. bartramii* production.

2 Materials and methods

2.1 *Catch data and SST data*

The squid jigging data during 1998 to 2004 used in this study came from Chinese Squid Jigging Technical Group, including catch per fishing vessel and day. And there were 167 116 samples in total involved in this study. The monthly SST data from August to November of 1998–2004 in the Northwest Pacific Ocean were derived from the Ocean Watch database of the NOAA (http://oceanwatch.pifsc.noaa.gov/). The temporal resolution is month and the spatial resolutions is 0.5°. In order to get the proper temporal and spatial resolution, the original data by day were averaged into the data by month and the original spatial data which the resolution was 0.3° was also averaged into the data which resolution was 0.5 also using R program.

The average catch per fishing day for *i* month ($CPUE_i$, t/d) in one fishing area (0.5°×0.5°) is calculated as

$$CPUE_i = \frac{C_{pi}}{F_i}, \tag{1}$$

where C_i represents the total catch in the fishing area 0.5°×0.5° for *i* month; and F_i represents the fishing days in the fishing area 0.5°×0.5° for *i* month.

2.2 *Estimation of potential habitat for O. bartramii*

The CPUE is an important indicator of fisheries abundance (Zhou et al., 2004; IPCC, 2007). A histogram analysis of the SST data corresponding to the CPUE values was used to determine the monthly SST preference of *O. bartramii* in the Northwest Pacific Ocean. The identified range of the preferred SST was used as a threshold for selecting and predicting potential habitats of *O. bartramii* in the Northwest Pacific Ocean. Marine Explore software was used to plot the figures of the potential habitats of *O. bartramii* and the corresponding areas are also calculated by using the Marine Explore.

2.3 *Increase in SST from climate-change and its effects on habitats of O. bartramii*

This study considered several scenarios of the SST increases developed based on global climate simulations under several emission scenarios (A1FI, A1B, A1T,A2, B1, and B2) from the AR4 of the IPCC (IPCC, 2007). For each scenario, the potential impact on the habitats of *O. bartramii* in the Northwest Pacific Ocean for the next 100 a was examined. These six climate-change scenarios include most likely scenarios for global surface warming of 1.80–4.08°C, based on the relationships between the forces driving greenhouse gas and aerosol emissions and their global evolution during the 21st century (IPCC, 2007). Each scenario represents different demographic, social, economic, technological, and environmental developments (IPCC, 2007). SST increases of 0.5, 1.0, 2.0, and 4.0°C were simulated to examine the effects of possible climate changes on the displacements of potential habitats of *O. bartramii* in the Northwest Pacific Ocean. In order to get simulate SST, we used the original SST values plus the four scenarios of the SST increases (0.5, 1.0, 2.0, and 4.0°C) respectively to get four new SST value sets which called SST plus 0.5, SST plus 1.0, SST plus 2.0, SST plus 4.0°C. Then the potential habitats of red flying squid in the Northwest Pacific Ocean were mapped using the same SST preferences mentioned in section 3.2 from four new SST value sets so as to see the influence of SST increase on the potential habitats.

3 Results

3.1 *Monthly CPUE and habitat distribution of O. bartramii*

The average monthly and yearly CPUE of *O. bartramii* during 1998 to 2004 were described in Fig. 1. A time period from August to November was the peak fishing season and had a monthly average CPUE of higher than 2.3 t/d (Fig. 1a). For the yearly CPUE of *O. bartramii* from August to November 2001 got the lowest CPUE value and 2004 got the highest CPUE value in August and September (Fig. 1b and c). In October, the lowest CPUE value was in 2000 and the highest CPUE value was in 2003 (Fig. 1d). In November, the lowest CPUE value was in 2000 and the highest CPUE value was in 1999 (Fig. 1e).

The overall average CPUE of *O. bartramii* during 1998 to 2004 was mapped to examine the spatial distribution of the traditional habitats of squid in the Northwest Pacific Ocean (Fig. 2). The habitat of this squid during August to November is located within the longitude range of 145°–170°E (Fig. 2).

3.2 *SST preferences and habitat of O. bartramii*

The monthly average SST for *O. bartramii* in the Northwest Pacific Ocean ranged between 12°C and 23°C during 1998 to 2004. And the monthly SST preferences of *O. bartramii* were examined using a histogram analysis (Fig. 3). The results show that the ranges of the SSTs in the four months for *O. bartramii* in the Northwest Pacific Ocean are 15–23°C in August, 15–23°C in September, 12–21°C in October, and 10–16°C in November, respectively.

The monthly production values of *O. bartramii* in the Northwest Pacific Ocean were overlaid on the corresponding satellite SST images for the time period from August to November (Fig. 4). A strong association between the SSTs and the CPUE of *O.*

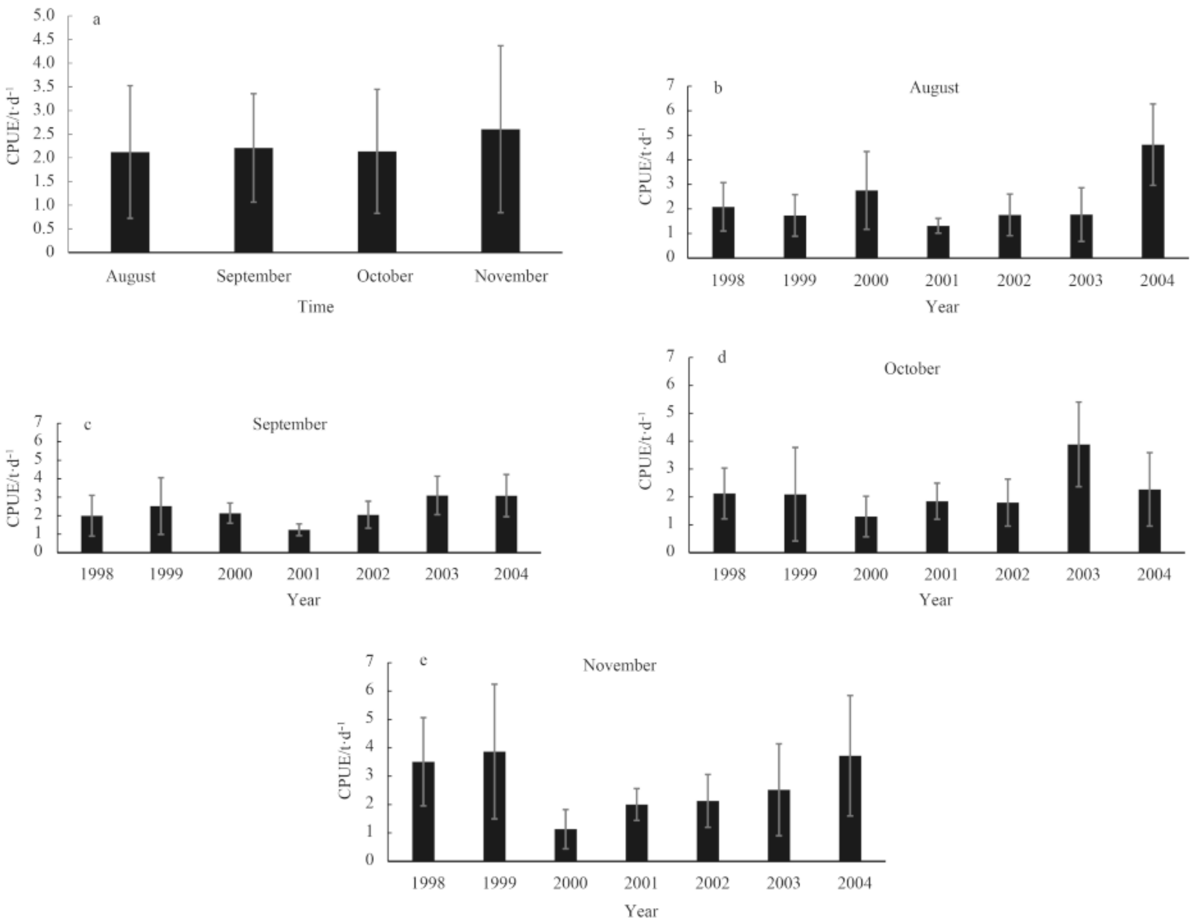

Fig. 1. Monthly average CPUE values of neon flying squid (*Ommastrephes bartramii*) in the Northwest Pacific Ocean during 1998–2004 (a) and yearly average CPUE values of neon flying squid (*O. bartramii*) in the Northwest Pacific Ocean from August to November (b–e). The bar indicates the standard deviation of the average CPUE values.

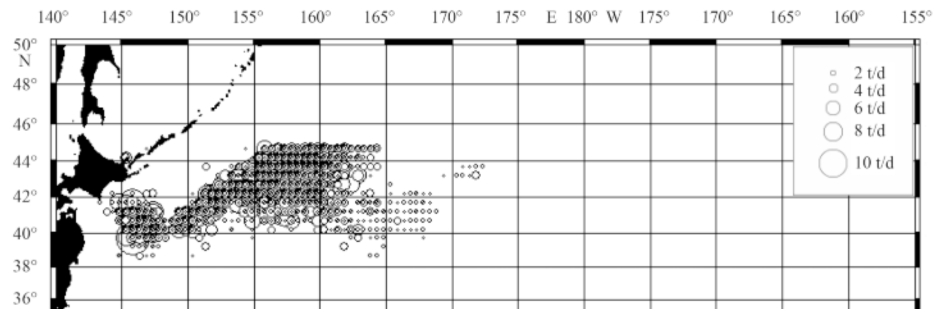

Fig. 2. Spatial distribution of overall average CPUE values of neon flying squid (*Ommastrephes bartramii*) fishery in the Northwest Pacific Ocean during 1998–2004. The circle size represents the size of the CPUE value.

bartramii was found in the Northwest Pacific Ocean: the range of SSTs was 15–23°C in August, 15–23°C in September, 12–21°C in October, and 10–16°C in November, and the corresponding CPUE values were 15.75 t/d in August, 15.25 t/d in September, 17.40 t/d in October, and 12.75 t/d in November, respectively. Most important of all, almost all the CPUE values were in the area of the SST preferences of *O. bartramii* which indicated that the preferable SST values are a good indicator classifying the quality of habitats for *O. bartramii* (Fig. 4).

3.3 *Effects of climate change on potential habitats of O. bartramii*

The monthly maps of the potential habitats were developed for *O. bartramii* in the Northwest Pacific Ocean based on the corresponding SST preferences under the conditions of the study

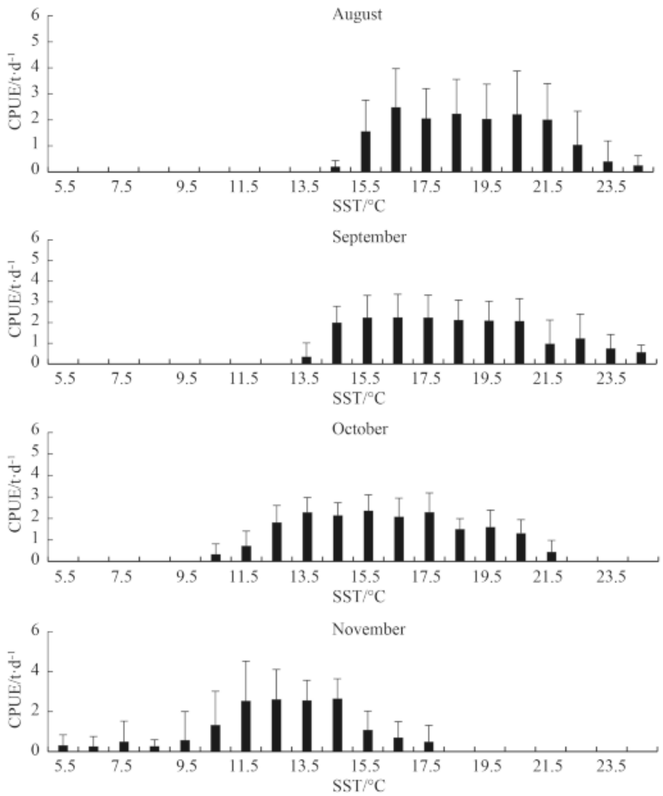

Fig. 3. Monthly favorable SSTs of neon flying squid (*Ommastrephes bartramii*) in the Northwest Pacific Ocean using a histogram analysis during 1998–2004.

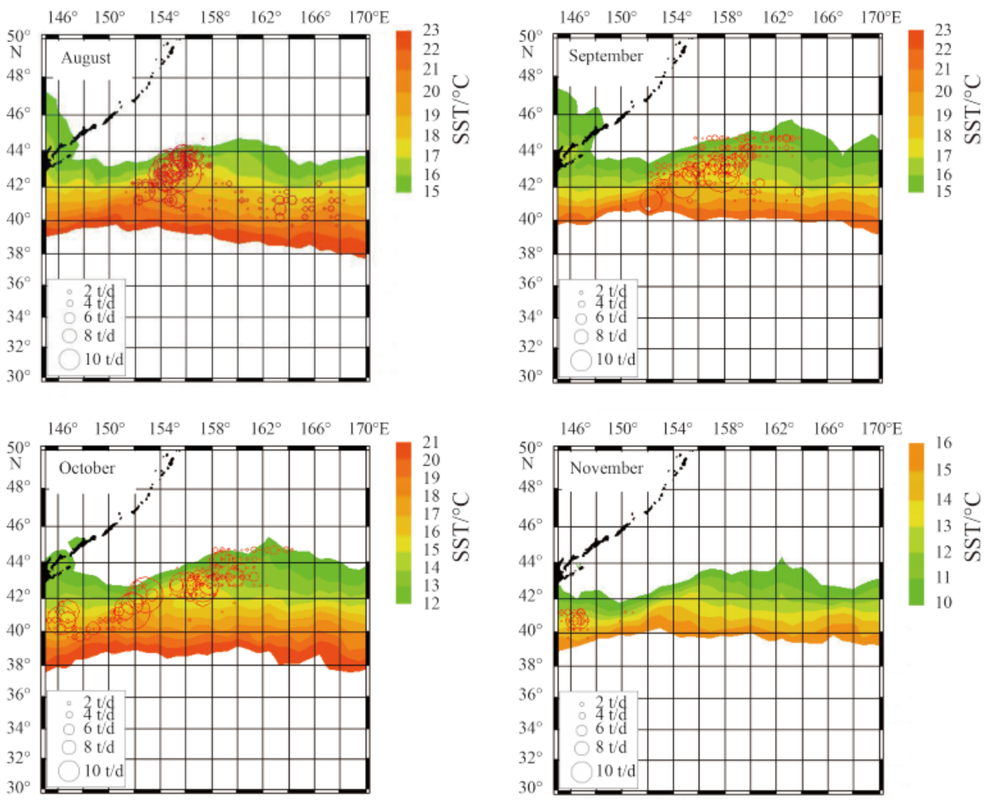

Fig. 4. Production values of neon flying squid (*Ommastrephes bartramii*) in the Northwest Pacific Ocean (red circles) from August to November in association with satellite SST images.

years (1998–2004) and the scenarios of 0.5, 1.0, 2.0, and 4.0°C increases in SSTs (Fig. 5). The potential habitats were progressively concentrated into larger horizontal belts from the early stage (August) to the end of the fishing season (November) (Fig. 5).

The quantitative analysis of the potential habitats of *O. bartramii* in the Northwest Pacific Ocean was also conducted based on the SST preferences to examine the temporal and spatial variations of the habitat. During the fishing season for *O. bartramii*, the potential habitats for all five scenarios displayed a southward latitudinal shift from August to November (Fig. 6). In August, the southernmost boundary lines of potential habitat extended from 37.5°N in the study years to 42.5°N under the climate change scenario of a 4.0°C increase in the SSTs. An obvious pole ward shift in the potential habitats of *O. bartramii* would

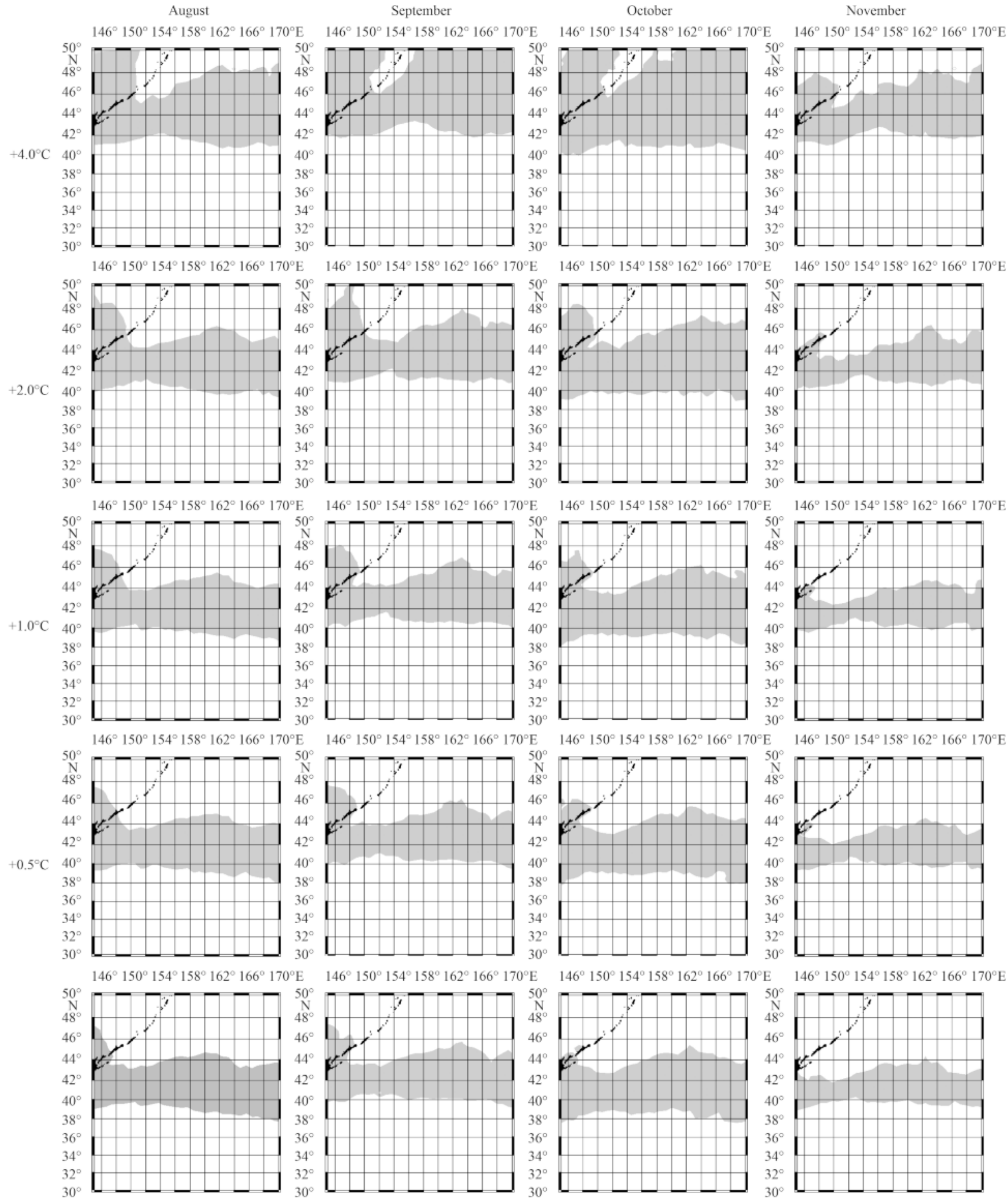

Fig. 5. Monthly (August–November) potential habitats of neon flying squid (*Ommastrephes bartramii*) in the Northwest Pacific Ocean derived from satellite SST data for study years (1998–2004) and with SST increases of 0.5, 1.0, 2.0, and 4.0°C.

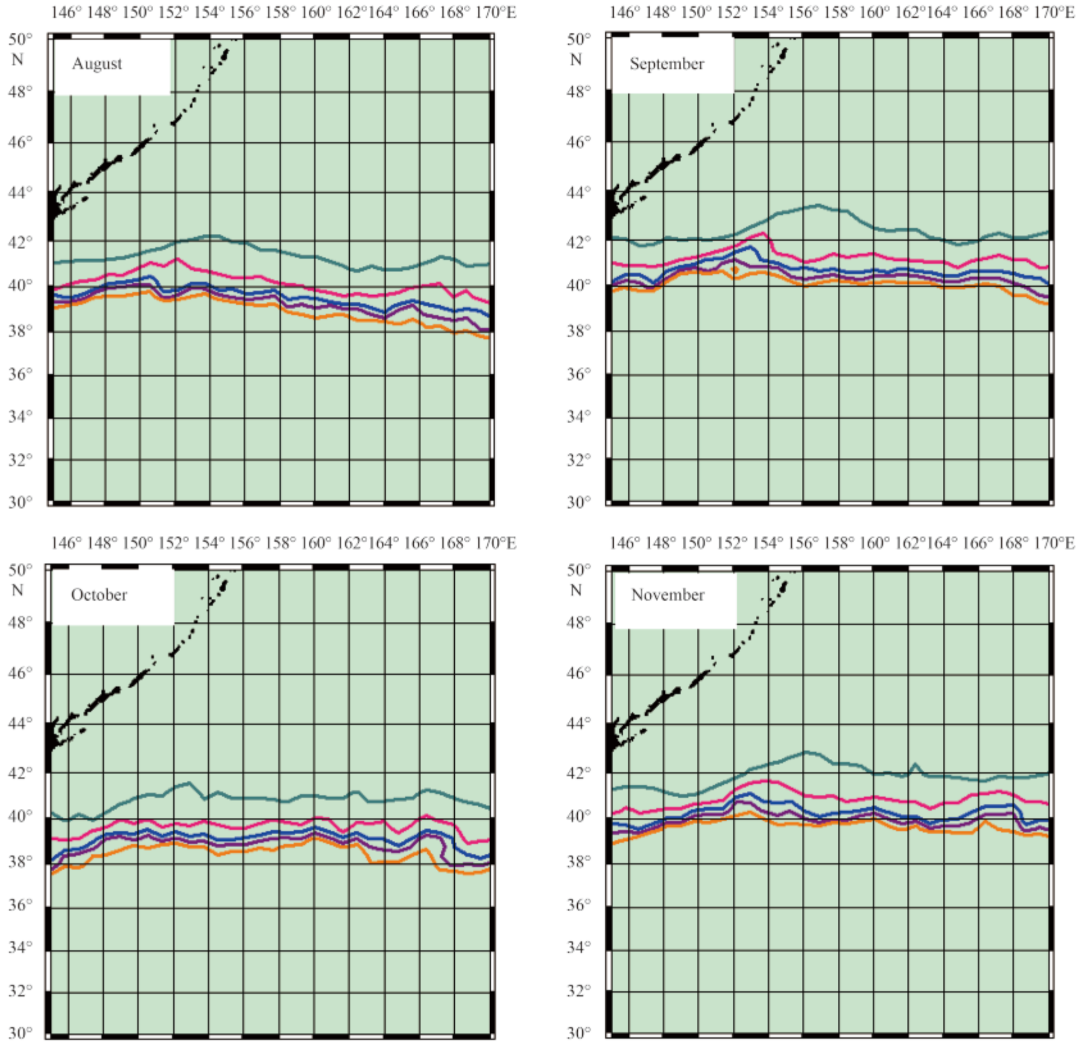

Fig. 6. The southernmost boundaries (yellow line is the southernmost boundaries for SST, purple line is the southernmost boundaries for SST plus 0.5°C, blue line is the southernmost boundaries for SST plus 1°C, pink line is the southernmost boundaries for SST plus 2°C, and green line is the southernmost boundaries for SST plus 4°C) of potential habitats of neon flying squid (*Ommastrephes bartramii*) in the Northwest Pacific Ocean, August–November, under SST increases of 0.5, 1.0, 2.0, and 4.0°C, based on the six climate change scenarios (A1FI, A1B, A1T, A2, B1 and B2) (IPCC, 2013).

happen between original conditions and the four different climate change scenarios with the SST increases of 0.5, 1.0, 2.0, and 4.0°C (Fig. 6). The largest monthly maximum latitudinal displacements happened between the 4.0°C scenario and the study years. Changes of 3.5° latitude were noted for October, of 4° latitude for September and November and 5° latitude for August. The areas of the monthly potential habitats of *O. bartramii* during 1998–2004 were considered as the base case (Table 1). The area of the potential habitats for *O. bartramii* increased with increase in a SST of 0.5, 1.0, 2.0, and 4.0°C in September and October. In August, however, the areas decreased when the SSTs increased from 0 to 0.5, 1.0 and 2.0°C, but had a large expansion with an increase of 4.0°C in the SST. In November, the area in the SST plus 0.5°C is smaller than the area in the original SST (Table 1).

Table 1. Monthly (August-November) area changes of neon flying squid (*Ommastrephes bartramii*) in the Northwest Pacific Ocean with an increase in SST of 0.5, 1.0, 2.0, and 4.0°C during 1998–2004 (as part of marine explore output)

SST/°C	August		September		October		November	
	Area/km²	Ratio of area increase/%	Area/km²	Ratio of area increase/%	Area/km²	Ratio of area increase/%	Area/km²	Ratio of area increase/%
SST	1 141 346		954 568		1 262 394		763 555	
SST+0.5	1 116 873	–2.19	959 626	0.53	1 262 959	0.04	769 373	0.76
SST+1.0	1 115 706	–0.10	981 405	2.22	1 266 479	0.28	769 293	–0.01
SST+2.0	1 092 532	–2.12	1 020 627	3.84	1 335 451	5.16	822 407	6.46
SST+4.0	1 173 772	6.92	1 228 922	16.95	1 526 277	12.50	975 576	15.70

4 Discussion

There are two main currents, the warm Kuroshio Current and the cold Oyashio Current, meet in the Northwest Pacific Ocean (Chen et al., 2012). The Kuroshio Current is characterized by warm (15–30°C) and high-salinity water (34.5–35.0), (Wang and Chen, 2005). To the contrary, the Oyashio Current is featured by cold and hypothaline water (Wang and Chen, 2005). The interplay of these two currents forms fronts and eddies, which are the preferred environmental condition for *O. bartramii* (Chen et al., 2011). The dynamic physical oceanographic structures, such as eddies and frontal zones, create a highly productive habitat. This environmental condition is favorable feeding ground for many commercially important species, such as Pacific saury (*Cololabis-saira*), anchovy (*Engraulis japonicus*), and albacore (*Thunnus alalunga*) (Pearcy, 1991; Zainuddin et al., 2006).

In this study, the monthly production values associated with the SST data of *O. bartramii* (Fig. 4) indicated a possible linkage between potential habitats of *O. bartramii* and the spatial variations in the Northwest Pacific Ocean. Chen et al. (2012) calculated the monthly latitudinal center of gravity of CPUE ($LATG_j$) and analyzed the relationship between the strength and position of the Kuroshio and the spatial distribution of *O. bartramii*. They suggest that the varying strength of the Kuroshio leads to changes in the environmental conditions at 40–43°N and 150–155°E. The environmental variable most significantly correlated with $LATG_j$ was the SST, suggesting that the distribution of *O. bartramii* is mainly controlled by a thermal habitat.

In this study, the relationship between SST and CPUE was used to estimate the preference SST ranges of *O. bartramii* in the Northwest Pacific Ocean, and mapped the monthly spatial distribution of their preference habitats, which is consistent with the temporal and spatial distributions of the red flying squid in the Northwest Pacific Ocean. Little variation was found among the monthly distributions of *O. bartramii* (Fig. 2). This phenomenon might result from the limitation of the fishing areas. The data used are derived from commercial fishery, and these data reflect not only fish abundance but also fishermen's behavior for optimal economic return from the fishery (Swain and Wade, 2003; Tian, 2006).

In the open ocean, the preferred water temperature of a fish species is usually found in a limited range (Wadley and Lu, 1983; Chen et al., 2011). The SST is a convenient proxy or indicator of the potential habitats of *O. bartramii* in the Northwest Pacific Ocean (Wang and Chen, 2005; Chen et al., 2010). However, other environmental factors might also affect the spatio-temporal distributions of *O. bartramii* in the Northwest Pacific Ocean. Thus, the role of other variables, such as changes in the peak fishing season, seasonal variations in SST increases, distributions of prey and predators, needs to be considered in the evaluation of potential impacts of climate changes on the habitats of *O. bartramii*.

Based on the four scenarios of SST increases (+0.5°C, +1°C, +2°C and +4°C) which is from the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), we conclude that the preference habitats of *O. bartramii* in the Northwest Pacific Ocean are likely to undergo a poleward displacement in response to SST variability attributable to global warming and the habitat for this species will expand in most predicted scenarios. This is consistent with the conclusion derived in other studies that many marine populations are likely to expand northward to higher latitudes because of global warming (Kuwahara et al., 2006; Stenevik and Sundby, 2007; Mueter et al., 2009; Van Hal et al., 2010; Chen et al., 2011).

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