Indian Journal of Geo Marine Sciences
Vol. 48 (04), April 2019, pp. 444-451

Bigeye tuna fishing ground in relation to thermocline in the Western and Central Pacific Ocean using Argo data

Shenglong Yang[1,2]*, Bianbian Zhang[2], Heng Zhang[2], Shengmao Zhang[2], Xiumei Fan[2], Chenjun Hua[2], & Wei Fan[2]

[1]College of Marine Sciences, Shanghai Ocean University, Shanghai- 201306, China

[2]Key Laboratory of East China Sea & Oceanic Fishery Resources Exploitation and Utilization, Ministry of Agriculture, P.R. China, Shanghai-200090, China

*[E-mail: ysl6782195@126.com]

Received 11 September 2017; revised 11 May 2018

The relationship beween thermocline and bigeye tuna (*Thunnus obesus*) fishing grounds in the Western and Central Pacific Ocean was evaluated by Argo data and monthly CPUE (catch per unit effort). The generalized additive model indicated evidence of nonlinear relationships between CPUE and six thermocline characteristics. The results suggested that the fishing grounds distributed where the upper boundary temperature was about 26 ºC and the upper boundary depth values between 70 and 100 m. The fishing grounds located between the two high value shapes of the lower boundary depth of thermocline, if the depth was >300 or <150 m, the CPUE tended to be low. The lower boundary temperature of the thermocline in the fishing grounds was lower than 13 ºC. Conversely, if the temperature was higher than 17 ºC, the hooking rates were very low. The strongest relationship between CPUE with thermocline thickness and thermocline strength was approximately at 60 m and 0.1 ºC/m. The optimum ranges for the upper boundary thermocline temperature and depth and the lower boundary thermocline temperature and depth, thermocline thickness and thermocline strength were between 26-29 ºC, 70-110 m, 11-13 ºC, 200-280 m, and 0.01-0.15 ºC/m, 60-80 m, respectively.

[**Keywords:** *Bigeye; Thermocline; Temporal-spatial distribution]*

Introduction

Bigeye tuna (*Thunnus obesus*) inhabit tropical and temperate waters in the world, and are commercially very important. Understanding the knowledge of movements and habitat preferences of bigeye tuna enables improving the efficiency of the long-line fleet, aiding in resource management and sustainable use of fisheries resources[1]. Bigeye tuna can be deep swimmer and highly mobile, which allows them have distinctive depth distribution and vertical movement patterns[2,3,4,5,6,7,8,9&10]. They remain in the uniformed temperature surface layer at night and can descend to greater than 500 m depth at dawn. While exhibiting non-associative behavior, they descend below the thermocline (Z20, the depth of the 20 °C isotherm) to forage the small nektonic organisms of the deep scattering layer (DSL)[2,3,4,5,6,7,8,9&10]. Bigeye tuna are caught mainly by longline, especially for adult fish. The efficiency of longline gear differs depending on the depth of hooks and their relationship with the depth of fish[1]. The vertical pattern of water temperature, especially thermocline distribution play a key factor in the fishing grounds distribution of bigeye tuna[10,11,12&13]. So identifying the vertical distribution of Bigeye tuna improves our understanding of longline catches and provides critical information for fisheries management and resource conservation. But, there is little literature about the relationship between thermocline and bigeye tuna in the Western and Central Pacific Ocean (WCPO), which accounts for close to half of the worlds tuna production. Therefore, for analyzing the spatial-temporal distribution of thermocline, the empiric correlation between the spatial distribution of bigeye tuna and thermocline in the WCPO to understand the horizontal and vertical of bigeye tuna population is very important.

The Argo floats data to describes the ocean variability and have been used extensively in different oceanic studies in recent years, but as yet have been seldom used in pelagic fishery research[14&15]. In this paper, we adopted Argo profile buoys data, evaluated the isoline distribution of thermocline characteristics, calculated the optimum ranges of thermocline characteristics of the central fishing grounds and aided tuna resource management in WCPO.

Materials and Methods

In this paper, two types of data set were used: fishery and Argo buoys. Bigeye tuna inhabit tropical and temperate waters in the world, particularly for the tuna longline fishery in the tropical area. To meet the objectives of this study, the location (130°E-130°W, 25°S-25°N) was used as the study area.

The catch and effort data were compiled from WCPFC, from 2007 to 2016. They include the number of hooks, fishing time, longitude and latitude, and catch of bigeye tuna. The spatial resolution is 5°×5° and the temporal resolution is a month. The use of 5° grids is a conventional method to deal with tuna catch data. Our data were standardized by CPUE, and this bias was negligible[16].

In this paper, the Argo buoys data of the world during 2007-2016 were collected to calculate subsurface environmental (http://argo.org.cn/english/). The Argo buoys data of the website contains all the Argo buoys of the worlds (www.argo.ucsd.edu). All the temperature profiles were first interpolated to 2 m using Akima interpolation methods before calculating the thermocline characteristics. According to the method developed by Zhou[17], the low standard value of the thermocline intensity (0.05 ºC/m) was taken to identify the thermocline characteristics (the upper and lower boundaries temperature and depth, thermocline thickness and thermocline strength) by step-wise discriminant analysis, using standard computation and determination methods[12].

We extracted all the scatter values at the upper and lower boundaries temperature, thermocline thickness and thermocline strength in horizontal direction of all year and month and grouped by month, then calculated the contour values with 1°×1° spatial resolution by Kriging methods and plotted the monthly distribution maps of thermocline characteristics. To match the fishery data, all environmental data were averaged into 5° squares in spatial.

This paper took the monthly CPUE of longline bigeye tuna and monthly thermocline characteristics values to investigate the relationship between the fishing grounds distribution of bigeye tuna and thermocline. This method had been used in the tuna preference in several literatures. According to the methods developed by Levitus[18], the seasons were divided as follows: January to March as boreal winter, April to June as boreal spring, July to September as boreal summer, and October to December as boreal autumn.

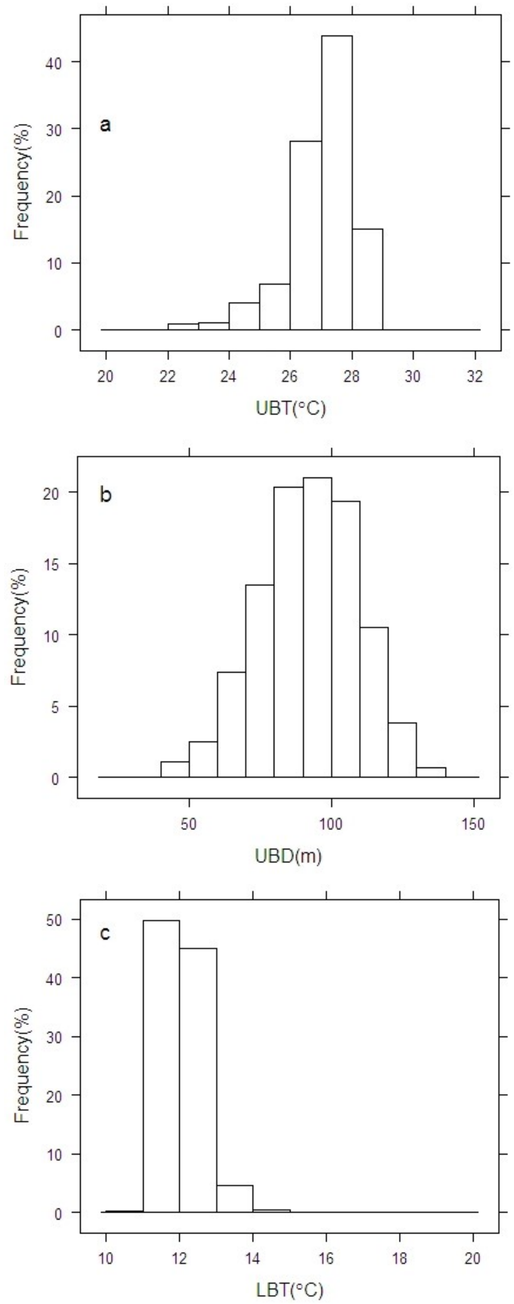
The CPUE was used as a relative abundance index of bigeye tuna. It was calculated as the number of individuals caught per 1000 hooks (103 fish hook-1) on a 5°×5° grid, and values averaged monthly for the data were spatially scattered and not evenly distributed. To investigate monthly distribution patterns, we calculated the mean CPUE for all years in all grids. Matlab soft were was used to create average CPUE distribution maps. We pooled monthly data and calculated the 3rd quartile. We selected the 3rd quartile (Q3=4.11) as the threshold. According to Zainuddin[19], the CPUE data were divided into three categories: Null CPUEs, positive CPUEs, and high CPUEs. For this study, bigeye tuna CPUE were divided into three cases: (1) Cases with CPUE equal to zero – 'null CPUEs'; (2) Cases with CPUE greater than zero but lower than 4.42 – 'positive CPUEs'; and (3) Cases with CPUE greater than 4.11 – 'high CPUEs'. We define the high CPUEs regions, i.e., hotspots or good fishing zones. In the present study, we used the high CPUE data analysis to estimate optimum ranges of subsurface oceanographic variables.

We plotted the upper and lower boundaries temperature and depth, thermocline thickness and thermocline strength contour on a spatial overlay map to characterize the hotspots, and to determine the relationship between bigeye tuna distribution and thermocline characteristics. Preferred oceanographic conditions were obtained by considering confidence ranges of both the high CPUE data (mean±one standard deviation) and empirical cumulative distribution function (ECDF; the specific value of variables at D(t) max±one standard deviation) during 2007-2016. We matched both these ranges to determine the preferred ranges of the six environmental (the upper and lower boundaries temperature and depth, thermocline thickness and thermocline strength) conditions[19]. Using ECDF, we analyzed stronger association between six oceanographic variables and bigeye tuna CPUE during the same periods.

In addition, a generalized additive model (GAM) was used to examine the nature of the relationship between CPUE and the thermocline. Following Maury et al[20], we assumed a normal distribution for the log of CPUE+1. All explanatory variables were modeled as a spline function. The GAM model was constructed in the R programming environment using the GAM function of the MGCV package[21]. Model selection was performed manually, and we retained candidate predictors that were significant, minimized the Akaike Information Criteria (AIC) and increased the amount of explained deviance.

Results

he frequency graph suggests that the central fishing grounds in the areas where the upper boundary temperature ranged from 20 to 28.9 ºC (Fig. 1a), 87.9% of the highest CPUEs distributed between 26 and 28.9 ºC and tended to be located at 27 ºC. The lower boundary temperature were found in fishing grounds ranged from 10 to 19.9 ºC (Fig. 1b), 89.4% of the highest CPUEs distributed between 11 and 12.9 ºC. The histogram of high catch rates suggests that fishing tended to be centered at 11~13 ºC. The frequency of the upper boundary depth of high catch of bigeye tuna follows a Gaussian distribution. Distribution of high CPUEs in relation to the upper boundary depth ranged from 20 to 139m (Fig. 1c), 90.2% of the highest CPUEs distributed between 70 and 110 m (mode: 90 m). The highest CPUEs in fishing grounds occurred in areas where the lower boundary depth ranged from 140 to 299 m (Fig. 1d), 77% of the highest CPUEs distributed 200~279 m. The fishing grounds located in areas where



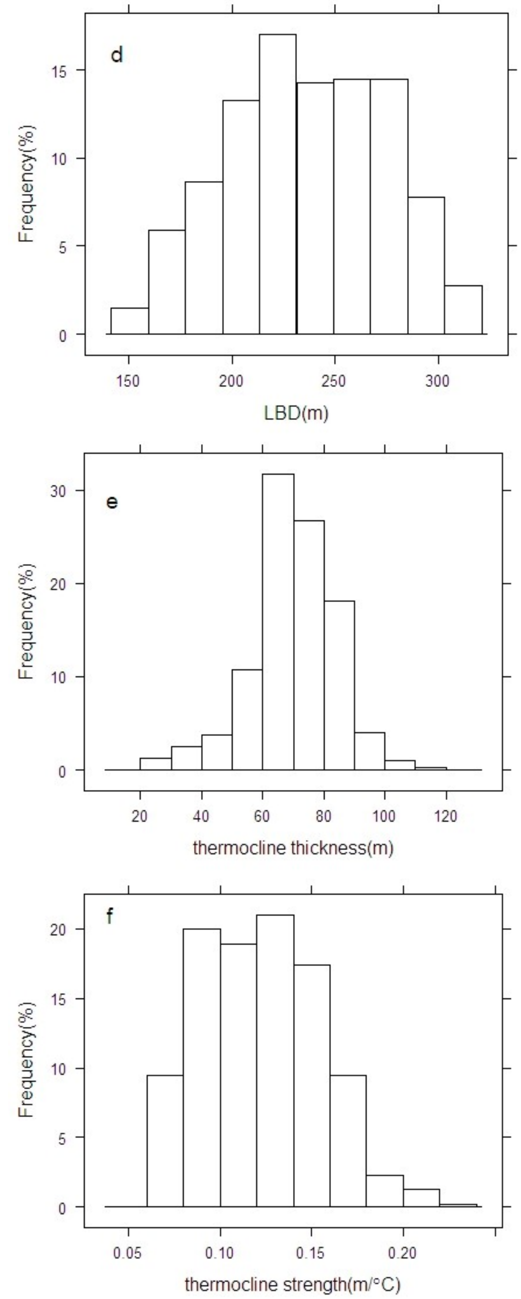
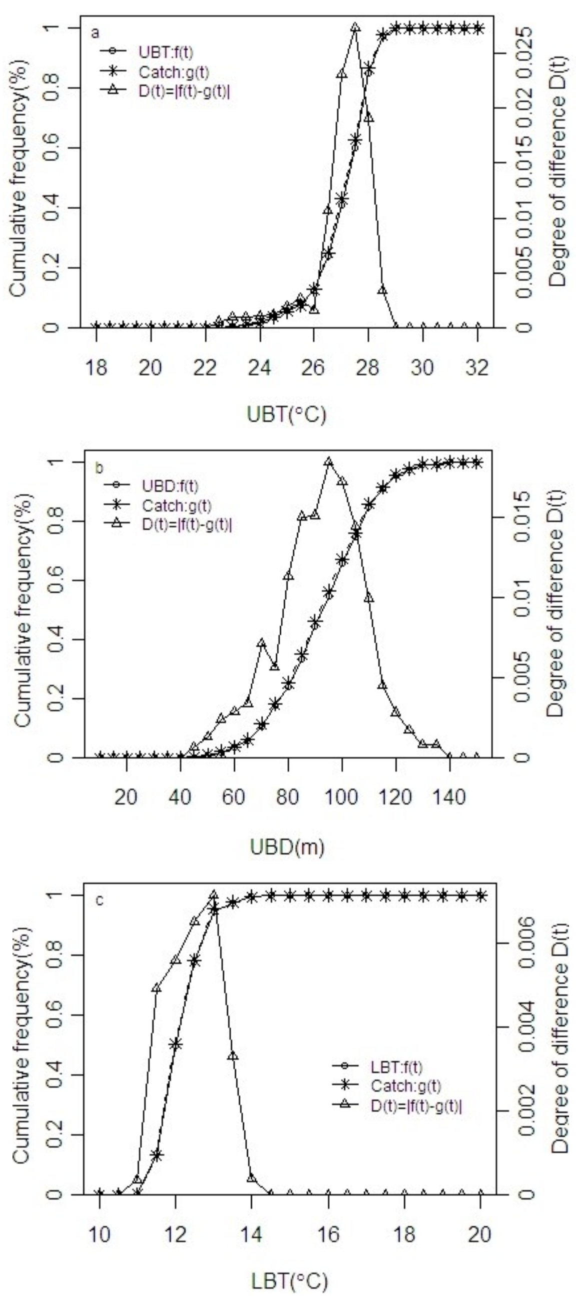


Fig. 1—Relationship between themocline variables and fishing frequency of high CPUE data for bigeye tuna CPUE during 2007-2016

thermocline thickness varied from 10 to 119 m (Fig. 1e), 80.1% of the highest CPUEs distributed between 50 and 89 m. The highest CPUEs in fishing grounds relation to thermocline strength obtained from 0.06 to 0.22 ºC/m (Fig. 1f). Most frequently distributed from 0.08 to 0.15 ºC/m.

From the results of ECDF, the relationship between high CPUEs and the thermocline variables reinforces the results obtained above. The cumulative distribution curves of the variables are different and the degrees of the difference between two curves (D(t)) were highly significant (P=0.05). The results suggest a stronger association between CPUE and thermocline variables, with the upper boundary temperature ranged from 26.82 to 29.17 ºC (28±1.17 ºC）(Fig. 2a), the lower boundary temperature ranged from 11.08 to 12.92 ºC（12±0.92 ºC）(Fig. 2b), the upper boundary depth ranged from 64.57 to 95.43



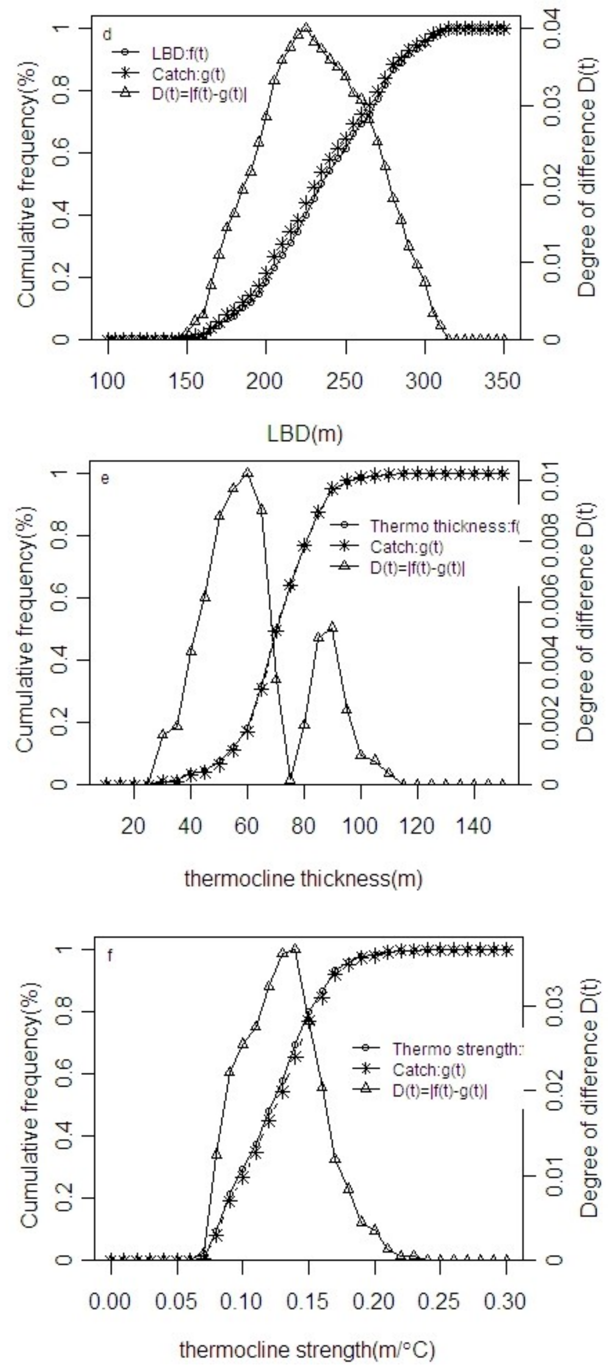


Fig. 2—Empirical cumulative distribution frequencies for themocline variables and fishing frequency of high CPUE data for bigeye tuna CPUE during 2007-2016

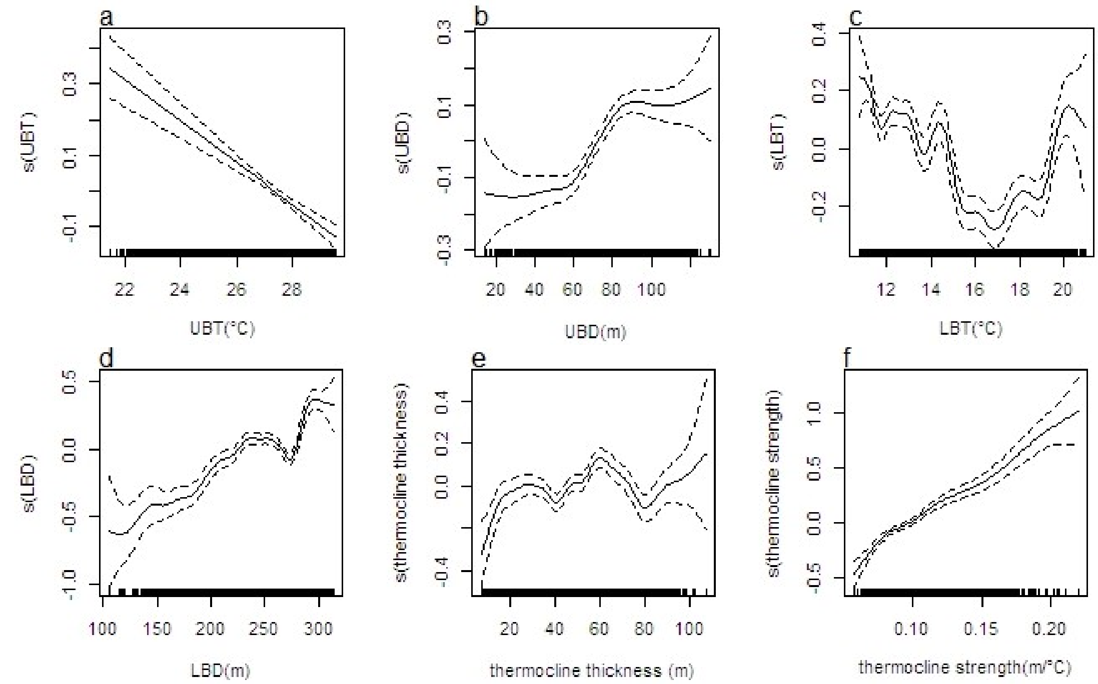


Fig. 3—The GAM derived effects of six thermocline variables on the potential vulnerability of bigeye tuna to long-line gear

m（80±15.43 m）(Fig. 2c), the lower boundary depth ranged from 204.12 to 275.88 m（240±35.88 m）(Fig. 2d), thermocline thickness ranged from 49.57 to 80.43 m (65±15.43 m) (Fig. 2e), thermocline strength ranged from 0.1 to 0.16 ºC/m (0.13±0.03 ºC/m) (Fig. 2f). The strongest associations between CPUE and the six variables occurred at 28 ºC (the upper boundary temperature), 13 ºC (the lower boundary temperature), 80 m (the upper boundary depth) , 240 m (the lower boundary depth), 65m (thermocline thickness) and 0.13 ºC/m (thermocline strength), respectively. If the thermocline is outside those favorable ranges, the Bigeye tuna catch rates tended to decrease.

The results of the GAM indicated that all the six thermocline predictor variables were highly significant ($p<0.001$) (Table 1). The table also showed that the model explained 86.8% deviance of all data and the adjust determination coefficient (adjR2) was 0.87.

The effect of the six variables on CPUE was nonlinear (Fig. 3). The hooking rates decreased as the upper temperature of thermocline became higher (Fig. 3a). The upper depth of thermocline had a dome-shaped effect, with depth below 60 m and over 120 m, CPUE tended to be few (Fig. 3b). The effect of D12 on the CPUE is shown in Fig. 3c, where the curve continuously decreases with a negative effect until 16 °C and then sharply increased while the lower temperature became higher, but the 95% confidence interval was relatively large. The CPUE increased with the lower depth of temperature, thermocline thickness and thermocline strength (Fig 3d, 3e, & 3f). Most catches were observed at deep depth of lower boundary. The strongest relationship between CPUEs with thermocline thickness and thermocline strength were approximately at 60 m and 0.1 ºC/m, respectively.

Table 1—The results of GAM

	edf	Ref.df	F	p-value
S (wd)	1.98	2.00	336.11	< 2e-16
S (sd)	7.17	8.24	4.05	7.41e-05
S (downwd)	8.33	8.87	68.76	< 2e-16
S (downsd)	8.33	8.88	13.70	< 2e-16
S (hd)	8.54	8.94	20.88	< 2e-16
S (qd)	0.96	8.08	30.37	< 2e-16

Discussion

Bigeye tuna inhabit tropical and temperate waters in the world, and spawned in warm water[16]. Obviously, the water temperature of bigeye tuna inhabit stratum influences the spatial distribution directly. Acoustic telemetry and archival tags researches have proved that bigeye tuna displayed a distinct diurnal shift in diving behaviour, generally diving at dawn to deeper, cooler waters and returning to shallower, warmer waters at dusk[2,3,4,5,6,7,8&9]. The thermocline plays a key role in decision making about vertical habitat preferences of bigeye tuna and influences the efficiency of longline gear.

Bigeye tuna remains in the shallow and warmer surface layer at night there by vertical distribution became narrow, which increases the vulnerability of tuna to surface fishing gears[22]. Evans[5] reported that there was a strong diurnal trend in bigeye catch rates, with catches from night sets generally higher than those from day sets. The optimum ranges for the upper boundary thermocline temperature and depth were between 26-29 ºC and 70-110 m in the paper, respectively. The results from archival tagging suggest that bigeye tuna vertical distributed between 24-26 ºC during night in the western Coral Sea and the Central North Pacific Ocean[5,8]. The highest hooking rates water temperature at night between 26-26.9 ºC from the results of longlines in Indian Ocean[23]. The results of this paper consistent with previous researches suggested that the upper boundary influced the distribution of bigeye tuna at night. The Figure 1 showed that CPUE is low in areas where the upper boundary temperature of thermocline was higher than 29 ºC or less than 25 ºC. Matsumoto reported negative correlation between the proportion distributed near the surface (0-30 m) and water temperature at depths of 20-30 m[9]. This may be the reason why CPUE is low in areas where the upper boundary temperature of thermocline is high. In addition, the diurnal migrate of bigeye tuna would influence the commercial catch rates.

Bigeye tuna spent 72% of the time below the thermocline to prey on the small nektonic organisms of the deep scattering layer during the day when exhibiting non-associative behaviors[7]. We could expect that the topology of low boundary of thermocline also impacts the spatial distribution of bigeye tuna population. Figure 1 and 3 suggest that the CPUEs were observed low in areas where low boundary depth of thermocline was deep and the low boundary temperature of thermocline was high. Most of the highest CPUEs were located in the grid where low boundary depth of thermocline was relatively shallow and the low boundary temperature of thermocline was low. This may relate to the prey strategy of tuna and longline fleet operation. In a warm and deep thermocline area, which suggests that the DSL in this area could be a much deeper water column, much deeper than the low boundary of thermocline in the daytime[24]. Thereby, the bigeye tuna needs to descend below the thermocline and explore deeper into the water column. Additionally, bigeye tuna are visual predators and opportunistic feeders; that light is presumably very dim at depths deeper than 300 m decreases the distinguishing capability of tuna. Multiple factors reduce bigeye tuna foraging opportunities in this area. It also reduces the vulnerability and exposure of tropical pelagic fishes to surface gear. The deep distribution of bigeye tuna (presuming there exists a bigeye population) absolutely exceeds the depth of hooks of most gears, which leads to the fact that the longline gear rarely captures bigeye tuna.

Bigeye tuna has the ability to dive deep into water and stays for a long time (2 h)[7]. Previous studies have stated that the bigeye has ability to swim in deep water, even exceeded 1900 m in the EPO[2,3,4,5,6,7,8&9]. Thought the vertical movements of bigeye tuna are also not restricted by the depth of thermocline in the WCPO, but exhaust lot of energy while crossing the thermocline. The thermocline thickness and thermocline strength play an inhibition role in bigeye habitat selection. That is why the CPUE increased with thermocline thickness and thermocline strength. But in the high value interval, the 95% confidence interval is large, not allowing a conclusive assessment of an increasing tendency.

In recent years Argo data have been applied to a wide range of ocean areas, yet very little information is available on fisheries. In this paper, we used Argo profile data to reconstruct the subsurface environment field and to reveal the habitat of bigeye tuna. Our results provide new insights into how oceanographic features influence the habitat of tropical pelagic fish and fisheries then exploit them by using a new tool (Argo profile data). Thus, the resolution of the subsurface environmental field may not compare well with the assimilation method, but it provides a convenient and effective way to investigate the habitat of tuna. However, the habitat of bigeye tuna is not defined by a single variable – temperature, depth at temperature, thermocline, oxygen, SSL distribution, and, undoubtedly, a host of other factors interact to define the habitat of bigeye tuna. Fortunately, most of the variables that may influence fish can be obtained by Argo data.

In this paper, the study was attempted in fisheries oceanography sciences to explore the empiric correlation between the spatial distribution of tuna and thermocline in WCPO. Remote sensing data, such as sea surface temperature (SST), chlorophyll-a concentration (CHL-a), sea surface salinity (SSS) and sea surface height anomaly (SSH), have been used frequently in describing tuna habitats in past as they are relatively easy parameters to obtain[25]. Most of the time bigeye tuna in WCPO remain shallow than 100 m, but deeper than 10 m, stay above thermocline or mixed layer[4]. So the upper boundary temperature of thermocline is better than SST. Tuna is in the top of the food chain in ocean, as it does bot feed on CHL-a directly. Water salinity is generally not considered to be a determinant of tuna. Arrizabalaga[26] use sea level anomaly as a proxy for variability of thermocline depth to investigate the effect on bigeye tuna. Compared to sea surface environments, the subsurface environment is more important, because the vertical excursions are likely to reduce the correlation of tuna catch with the surface environments. Studies proved that the depth of thermocline influences the catch rates of longline gears. Lan[27] conclude that higher subsurface water temperatures resulted in a deeper thermocline and caused a higher CPUE of yellowfin tuna. Maury[20] pointed out that thermocline depth has a monotonous positive effect on Japanese longliners and explains an important part of variance in the GAM model. The thermocline factors reveal the habitat of bigeye tuna.

The ability of bigeye tuna to tolerate lower ambient oxygen levels has also been reported to influence substantially the depth distributions of individuals. Although not treated in the present work, the relationship with oxygen concentration is probably important, especially for deep longline fisheries[27]. However, the relationships between the physiological mechanics of oxygen tolerance, oxygen uptake and temperature are highly complex in different oceans. In the WCPO, especially in the Western Pacific, the value of dissolved oxygen (DO) was sufficient for bigeye tuna and it seems that DO is not a limiting factor of diving in the area of this study[22]. It is likely that the vertical and horizontal distribution of bigeye in the WCPO also cannot be described using oxygen alone.

Conclusion

The present study reveals the relationship between the fishing grounds and thermocline in the Western and Central Pacific Ocean. There are significant seasonal variations in the upper boundary temperature and depth of thermocline in the central fishing grounds and significantly influenced the temporal and spatial distribution of the bigeye tuna population. The optimum ranges for the upper boundary thermocline temperature and depth and the lower boundary thermocline temperature and depth, thermocline thickness and thermocline strength were between 26-29 ºC ,70-110 m, 11-13 ºC, 200-280 m, and 0.01-0.15 ºC/m 60-80 m, respectively.

Acknowledgement

The research was supported by The Chinese National Natural Science Foundation (41606138) and the Special Funds of Basic Research of Central Public Welfare Institute (2015T06,2016Z01-02) and the Fund of Key Laboratory of Open-Sea Fishery Development, Ministry of Agriculture, P. R. China (LOF 2018-01).

References

1 Matsumoto, T., Saito, H., Miyabe, N., 2006: Swimming behavior of adult bigeye tuna using pop-up tags in the central Atlantic Ocean. *Collective Volume of Scientific Papers ICCAT*, 57(1): 151-170.

2 Dagorn, Lm.; Bach, P., Josse, E., 2000: Movement patterns of large bigeye tuna(*Thunnus obesus*) in the open ocean, determined using ultrasonic telemetry. *Marine Biology,* 136:361-371.

3 Musyl, M. K., Brill, R. W., Boggs, C. H., 2003: Vertical movements of bigeye tuna (*Thunnus obesus*) associated with islands, buoys and seamounts near the main Hawaiian Islands from archival tagging data. *Fish Oceanogr*, 12: 152-169.

4 Leroy, B.; Itano, D., Nicol, S., 2007: Preliminary analysis and observations on the vertical behaviour of WCPO Skipjack, Yellowfin and Bigeye Tuna in association with anchored FADs, as indicated by acoustic and archival tagging data. *WCPFC-SC3-BI SWG WP-4*.

5 Evans, K., Langley, A., Clear, N. P., Williams, P., Patterson, T., Sibert, J., Hampton, J., Gunn, J. S., 2008: Behaviour and habitat preferences of bigeye tuna (*Thunnus obesus*) and their influence on longline fishery catches in the western Coral Sea. *Canadian Journal of Fisheries and Aquatic Sciences,* 65(11): 2427-2443.

6 Schaefer, K. M., Fuller, D. W., Block, B. A., 2009: Vertical movements and habitat utilization of skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacares*), and bigeye (*Thunnus obesus*) tunas in the equatorial eastern Pacific Ocean, as ascertained through archival tag data. In: Nielsen, J. L.; Arrizabalaga, H.; Fragoso, N.; Hobday, A.; Lutcavage, M.; Sibert, J., (eds) Reviews: methods and technologies in fish biology and fisheries, vol 9, tagging and tracking of marine animals with electronic devices. *Springer*, Berlin, 121-144.

7 Schaefer, K. M., Fuller, D. W., 2010: Vertical movements, behavior, and habitat of bigeye tuna (*Thunnus obesus*) in the equatorial eastern Pacific Ocean, ascertained from archival tag data. *Marine Biology,* 157(12): 2625-2642.

8 Howell, E. A., Hawn, D. R., Polovina, J. J., 2010: Spatiotemporal variability in bigeye tuna (*Thunnus obesus*) dive behavior in the central North Pacific Ocean. *Progress in Oceanography*, 86:81-93.

9 Matsumoto, T., Kitagawa, T., Kimura, S., 2013: Vertical behavior of bigeye tuna (*Thunnus obesus*) in the

northwestern Pacific Ocean based on archival tag data. *Fisheries Oceanography*, 22(3):234-246.

10 Schaefer, K.M., Fuller,D.W., Hampton, J, Caillot, S., Leroy, B.M., Itano, D.G., 2015:Vertical movements, behavior, and habitat of bigeye tuna (Thunnus obesus) in the equatorial central Pacific Ocean, *Fisheries Research*,172:57-70.

11 Abascal, F.,J., Peatman,T., Leroy, B., Sicol, S., Schaefer, K., Fuller, D.W., Hampton, J., 2018:Spatiotemporal variability in bigeye vertical distribution in the Pacific Ocean. *Fisheries Research*, 204:371-379.

12 Yang, S. L., Zhang, Y., Fan, W.; Dai, Y., 2012: Relationship between the temporal-spatial distribution of fish in bigeye tuna fishing grounds and the thermocline characteristics in the tropical Indian Ocean. *Journal of Fishery Sciences of China*, 19(4): 679-689.

13 Li, Y. W., Song, L. M., Gao, P. F., 2012: Development of integrated habitat indices for bigeye tuna, Thunnus obesus, in waters near Palau. *Marine and Freshwater Research*, 63, 1244-1254.

14 Takano, A., Yamazaki, H., Nagai, T., 2009: A method to estimate three-dimensional thermal structure from satellite altimetry data. *Journal of atmospheric and oceanic technology,* 2655-2664.

15 Hartoko, A., 2010:Spatial distribution of Thunnus.sp,vertical and horizontal sub-surface multilayer temperature profiles of in-situ argo float data in indian ocean. *Journal of coastal development*, 41(1):61-74.

16 Lee, P. F.,Chen, I. C., Tzeng, W. N., 2005: Spatial and temporal distribution patterns of bigeye tuna (*Thunnus obesus*) in the Indian Ocean. *Zoological Studies*, 44(2): 260-270.

17 Zhou, Y, X., Li, B. L., Zhang, Y. J.; Ba, L. C., 2002: World oceanic thermocline characteristics in winter and summer. *Marine Science Bulletin*, 21(1): 16-22.

18 Levitus, S., 1983: Climatological Atlas of the world ocean. Eos, *Transactions American Geophysical Union,* 64(49): 962-963.

19 Zainuddin, M., Saiton, K.; Saiton, S. I., 2008: Albacore (*Thunnus alalunga*) fishing ground in relation to oceanographic conditions in the western North Pacific Ocean using remotely sensed satellite data. *Fisheries Oceanography*, 17(2): 61-73.

20 Maury, O., Gascuel, D., Marsac, F., Fonteneau, A., Rosa, A.L.D., 2001: Habitat and behaviour of yellowfin tuna Thunnus albacares in the Gulf of Mexico determined using pop-up satellite archival tags. *Canadian Journal of Fisheries and Aquatic Sciences*,58:458-469.

21 Wood S N. *Generalized Additive Models: An Introduction with R.* (CRC Press, Boca Raton, FL). 2006.

22 Prince, E. D., Goodyear, C. P., 2006. Hypoxia-based habitat compression of tropical pelagic fishes. *Fisheries Oceanography*, 15, 451-464.

23 Song, L., Gao, P. F., 2006: Captured depth, water-temperature and salinity of bigeye tuna (*Thunnus obesus*) longlining in Maldives waters. *Journal of Fisheries of China*, 30(3): 335-340.

24 Hazen, E. L.; Johnston, D. W., 2010: Meridional patterns in the deep scattering layers and top predator distribution in the central equatorial Pacific. *Fisheries Oceanography,* 19(6): 427-433.

25 Fan, W., Cui, X. S., Zhou, S. F., 2004: Preliminary study on the catch distribution of bigeye tuna (*Thunnus obesus*) longline and fishing grounds environment in the Pacific Ocean. *Marine Fisheries*, 26(4):261-265.

26 Arrizabalaga, H., Pereira, J. G., Royer, F., Galuardi, B., Goni, N., Artetxe, I., Arregi, I., Lutcavage, M., 2008: Bigeye tuna (*Thunnus obesus*) vertical movements in the Azores Islands determined with pop-up satellite archival tags. *Fisheries Oceanography*, 17(2): 74-83.

27 Lan, K. W., Lee, M. A., Lu, H. J.; Shieh, W. J., Lin, W.K., Kao, S. C., 2011: Ocean variations associated with fishing conditions for yellowfin tuna (*Thunnus albacares*) in the equatorial Atlantic Ocean. *ICES Journal of Marine Sciece*, 68(6), 1063-1071.