The relationship between the thermocline and the catch rate of *Thunnus obesus* in the tropical areas of the Indian Ocean

SONG Liming，ZHANG Yu，ZHOU Yingqi*

(College of Marine Science & Technology ,Shanghai Fisheries University, Shanghai 200090，China)

Abstract: To analyze and identify the relationship between the thermocline and the vertical distribution of bigeye tuna and to improve our understanding of bigeye tuna's behavior characteristics. Two surveys on tuna fishing ground were carried out on board of the longliners, *Huayuanyu No.18 , No.19* (September 15th～ Dec. 12th, 2005) and *Yueyuanyu No.168* (October 1st～ November 28th, 2006) in the tropical areas of the Indian Ocean to collect the environmental data. The depth and intensity of the thermocline were estimated from these data. The catch rates of bigeye tuna corresponded to the thermocline were calculated and analyzed, respectively. The results showed that a) the average catch rates of bigeye tuna below the thermocline was higher than that at the thermocline; b) the days, having catch rates at the depth below the thermocline higher than that at the thermocline, were accounted for 69.6%, 100% and 62.5% of all the surveying days of three longliners, respectively; c) by T-Test paired two samples for means, the overall average catch rates of bigeye tuna at and below the thermocline (in 2005) were no significant difference ($P=0.07>0.05$); the average catch rates of bigeye tuna at and below the thermocline (in 2006) were no significant difference either ($P=0.35>0.05$).

Key words: thermocline; *Thunnus obesus*; catch rate; longline; the tropical areas of the Indian Ocean

1 Introduction

The water depth which bigeye tuna (*Thunnus obesus*) inhabited is deeper than yellowfin tuna (*Thunnus albacares*), and it is less influenced by temperature grads, this is related to its physiological characteristics. When the thermocline is deepened, bigeye tuna may be generally deeper and less aggregated because of their extensive vertical migrations. Although the stock abundance may be unchanged, catchability and catch rate would likely be reduced. Conversely, when the thermocline is elevated, the habitat is generally shallower and the vertical migration less extensive. Bigeye tuna may be more aggregated, resulting in increased catchability and catch rate (PFRP,1999). Acoustic telemetry (Holland et al.,1990; Cayré,1991;Cayré and Marsac, 1993; Bach et al., 1998; Josse et al., 1998; Bertrand et al.,1999; Brill et al., 1999; Dagorn et al.,2000) and archival tags (Gunn and Block ,2001; Schaefer and Fuller, 2002; Musyl et al.,2003; Kitagawa et al.,2004) were widely used to study the vertical behavior of several tropical tuna species.

Temperature depth recorder (TDR) were fixed on the branch lines of the tuna longline, the

---

Foundation items: The project is granted by MOA funds of China under Program of Fishery Exploration in High seas in 2005 and 2006 (Project No.Z05-30 and No.Z06-33) , and Shanghai Leading Academic Discipline Project (Project No.T1101)

"Corresponding author: ZHOU Yingqi, Tel.: +86 21 65710392; fax: +86 21 65710203. *E-mail: yqzhou@shfu.edu.cn*.

actual hook depth and the hooked time could be measured, using tuna catch data of longline, the maximum depth of tuna hooked and their vertical distribution could be estimated. Compared to acoustic telemetry and archival tags, by means of this method the sampling data from different size of individuals and species in different conditions could be obtained (Saito,1975; Suzuki and Kume, 1982; Hanamoto,1987; Yamaguchi,1989; Nishi,1990; Boggs,1992; Bach et al.,1996; Bertrand et al.,2002) and the results were more close to actual fisheries situation. In this study, the depth and intensity of the thermocline were estimated. The catch rates of bigeye tuna corresponded to the thermocline were calculated and analyzed to identify the relationship between the thermocline and the vertical distribution of bigeye tuna and to improve our understanding of bigeye tuna's behavior characteristics. The results will be referenced for the study of its behavior characteristics, fishing activity and the conservation and management of fishery resources.

2 Material and methods

2.1 Fishing vessels, fishing areas and duration , fishing gear and method,

The sampling data collected on board of longliners *Huayuanyu No.18,19* (in 2005), as HY18 and HY19 at following, and *Yueyuanyu No.168* (in 2006), as YY168. The *HY18* and *HY19* have identical characters. i.e. vessel's length overall, registered breadth, registered depth, gross tonnage, net tonnage and main engine power is 26.12m, 6.05m, 2.70m, 150.00t, 45.00t and 407.00kW, respectively. The vessel characters of *YY168,* vessel's length overall, registered breadth, registered depth, gross tonnage, net tonnage and main engine power is 25.68m, 6.00m, 2.98m, 125.00t, 44.00t, 318.88kW, respectively. All longliners equipped with super spool.

The fishing activity of *HY18* and *HY19* was mainly limited within the area defined by 2°58′N～6°58′N，62°16′E～69°05′E and 5°26′N～8°03′N，61°58′E～70°29′E, respectively. Sampling sites are shown in Fig.1. The fishing activity of *YY168* was mainly limited within the area defined by 3º07′S～4º07′N，62º12′E～71º15′E. Sampling sites are shown in Fig.1.

In 2005, sampling duration was from Sep.15th ～ Dec.12th, and each boat fished for 48 days. In 2006, sampling time was from Oct. 1st～Nov. 28th, and the boat fished for 36 days.

In 2005, the longline gears consist of 3.6 mm diameter monofilament main line, 360mm diameter hard plastic floats, 5mm diameter nylon float line and 2 types of branch line ending in ring hook or circle hook. The length of main line, float line, branch line was 110km, 22m, and

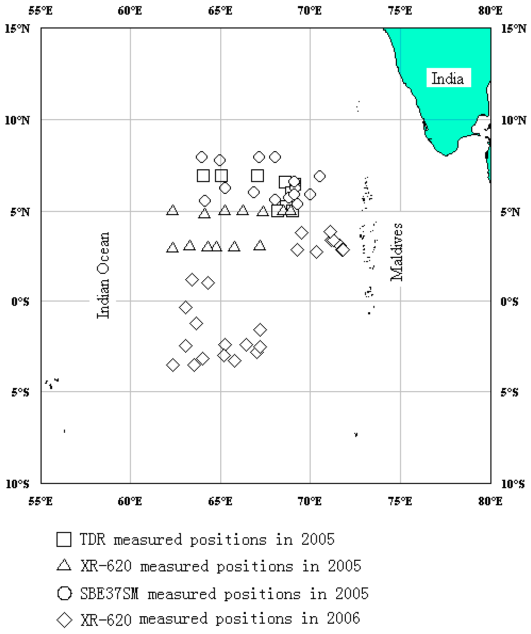


Fig.1 Sampling sites

16m, respectively. Two sets of fishing gear were used in the study. The conventional gears were used as the control group for comparisons of the other study. The experimental gears were assembled as 16 types of gear with 4 groups of messenger weight (0.5kgs, 1.0kgs, 1.5kgs and 2.5kgs in water). In general, the starting time of deploying gear was between 03:00 and 06:00 local time, and lasted for about 5 hours. The time of retrieving gear was between 12:00 and 15:00. Total operation would last for 10 to 12 hours. During the deployment, the vessel's speed was about 4.3 m.s^{-1}, line shooter speed was at 6.2 to 7.0 m.s^{-1}, and time interval between deploying fore and after branch lines was about 7.8 s. The length of main line between two branch lines was 43.5 m and there were 25 hooks between two floats (HBF). In 2006, the fishing gear configuration and fishing method were the same as that of the 2005 except for the length of the float line (30m) , branch line (18m) or the messenger weight (1.0kgs, 1.5kgs, 2kgs and 2.5kgs in water).

The data were recorded everyday including Submersible Data Logger (XR-620), CTD (SBE37SM) and TDR (2050) profiles, the species, number of fishing hooks, hook code which hooked fish.

The fishing boats were targeting bigeye tuna, and bycatch included yellowfin tuna, swordfish (*Xiphias gladius*), albacore (*Thunnus alalunga*) and billfish (Istiophoridae). Only the data, in which the catch rate was not 0, the code of hook hooked fish had been recorded and the water temperature profile was measured using XR-620, or SBE37SM or TDR-2050, will be used. So the available sampling days of longliners *HY18, HY19* and *YY168* were limited, only 23, 16 and 24 days, respectively. For longliners *HY18* and *HY19*, the numbers of hooked bigeye tuna were 171(folk length : 0.92m ～ 1.65m, round weight:15kg ～ 84kg) and 133(folk length : 0.73m ～ 1.81m, round weight : 9.5kg ～ 110kg), respectively, 304 in total. The numbers of hooked bigeye tuna whose hook code was recorded of *HY18* and *HY19* were 164 and 67, respectively, 231 in total. For longliner *YY168*, the numbers of hooked bigeye tuna were 175(folk length : 0.92m ～ 1.63m, round weight:16kg ～ 95kg) and all hook code at which they were hooked were recorded.

2.2 Instrumentation

Environmental sampling instruments include Submersible Data Logger XR-620, TDR (2050) (RBR Co., Canada), and SBE37SM (CTD, SeaBird Co., USA). In 2005, each boat was equipped with 7 TDRs. In 2006, there were 12 TDRs on the board. The measurement range of temperature of XR-620 is 5 to 35℃, the accuracy of data is 0.002℃. Depth measurement error of the TDR is within ±0.05% in depths of 10m-740m, temperature was measured to ±0.002℃. The temperature of the CTD was measured to ±0.002℃. Considering the accuracies of data from varied instruments and requirements of the study, we processed the data of depth and temperature to one effective decimal place, and catch rate to two decimals, respectively, in this study.

2.3 Data processing methods

The thermocline depth identification

The threshold standard of the thermocline was $|\Delta T/\Delta Z| = 0.05°C/m$. If the absolute value of vertical temperature gradient was higher or equal to $0.05°C/m$, the water layer was identified as “at the thermocline”. The upper and lower layer depth is the upper depth and lower depth of the thermocline, respectively (Bureau of technical supervision of the P.R of China, 1992).

The water temperature-depth data obtained by three equipments, the arithmetic average value of temperature and depth in 0m±5m,10m±5m, 20m±5m, 30m±5m… …400m±5m were calculated, respectively, and considering them as the standard temperature(denoted as T_j , *j*=0,1,2,3,……40) and standard depth(denoted as D_j , *j*=0,1,2,3,……40) as:

$$T_j = \frac{1}{n}\sum_{i=1}^{n} T_i \tag{1}$$

$$D_j = \frac{1}{n}\sum_{i=1}^{n} D_i \tag{2}$$

where T_i and D_i are the water temperature and depth data which measured in the standard depth of D_j.

The vertical temperature gradient bordering upon each other is calculated as:

$$G_j = \frac{T_{j+1} - T_j}{D_{j+1} - D_j} \tag{3}$$

where G_j is the vertical temperature gradient value between the standard depth D_j and D_{j+1}.

The upper and the lower layer of the thermocline were confirmed according to the standard of thermocline intensity.

The calculation of bigeye tuna's catch rate in various water layers

The catch rates of bigeye tuna at or below the thermocline were calculated respectively. The number of hooks (denoted as f_l) sampled in every water layer were calculated according to the predicted hook depth. In 2005, the predicted hook depth equations of the conventional gear and experimental gear were shown in (4) and (5) (Song et al., 2006).

$$\overline{D} = 0.30 + 0.67D_T + 1.03V_w^2 + 47.21\sin Q_W \tag{4}$$

$$\overline{D} = 96.53 + 0.69D_T - 17.03W - 19.73V_g^2 \tag{5}$$

where $\overline{D}$ is the predicted hook depth , D_T is the theoretical hook depth (same as the bellow), V_w is the wind speed, V_g is the fishing gear drift velocity, Q_w is the angle between prevailing course in deploying gear and drifting direction of fishing gear and W is the weight of the messenger weight in the water.

In 2006, the predicted hook depth equations of the conventional gear were shown in (6)～(9); the predicted hook depth equations of the experimental gear were shown in (10)～(13) (Song et al., 2007).

$$\text{Group 1: } D_{fc}' = D_T \times Q_{c1} \tag{6}$$

$$Q_{c1} = -0.046 - 0.291\tilde{K}_{c1} - 0.01N_{c1} - 0.186\sin\gamma_{c1} \tag{7}$$

$$\text{Group 2: } D_{fc}' = D_T \times Q_{c2} \tag{8}$$

$$Q_{c2} = 0.289 - 0.291\tilde{K}_{c2} - 0.01N_{c2} - 0.186\sin\gamma_{c2} \tag{9}$$

where D_{fc}' was the predicted hook depth of the conventional gear, Q_{c1} and Q_{c2} was the hook depth ratio of the conventional gear for group 1 and 2, $\tilde{K}_{c1}$ and $\tilde{K}_{c2}$ was the parameter of current shear of the conventional gear for group 1 and 2, N_{c1} and N_{c2} was the hook number of the conventional gear for group 1 and 2, γ_{c1} and γ_{c2} was the angle between wind direction and prevailing course in deploying gear of the conventional gear for group 1 and 2.

Group 1: $D_{fe}' = D_T \times Q_{e1}$ (10)

$$Q_{e1} = -0.124 - 0.327\tilde{K}_{e1} - 0.02N_{e1} - 0.073\sin\gamma_{e1} \tag{11}$$

Group 2: $D_{fe}' = D_T \times Q_{e2}$ (12)

$$Q_{e2} = 0.207 - 0.327\tilde{K}_{e2} - 0.02N_{e2} - 0.073\sin\gamma_{e2} \tag{13}$$

where D_{fe}' was the predicted hook depth of the experimental gear, Q_{e1} and Q_{e2} was the hook depth ratio of the experimental gear for group 1 and 2, $\tilde{K}_{e1}$ and $\tilde{K}_{e2}$ was the parameter of current shear of the experimental gear for group 1 and 2, N_{e1} and N_{e2} was the hook number of the experimental gear for group 1and 2, γ_{e1} and γ_{e2} was the angle between wind direction and prevailing course in deploying gear of the experimental gear for group 1 and 2.

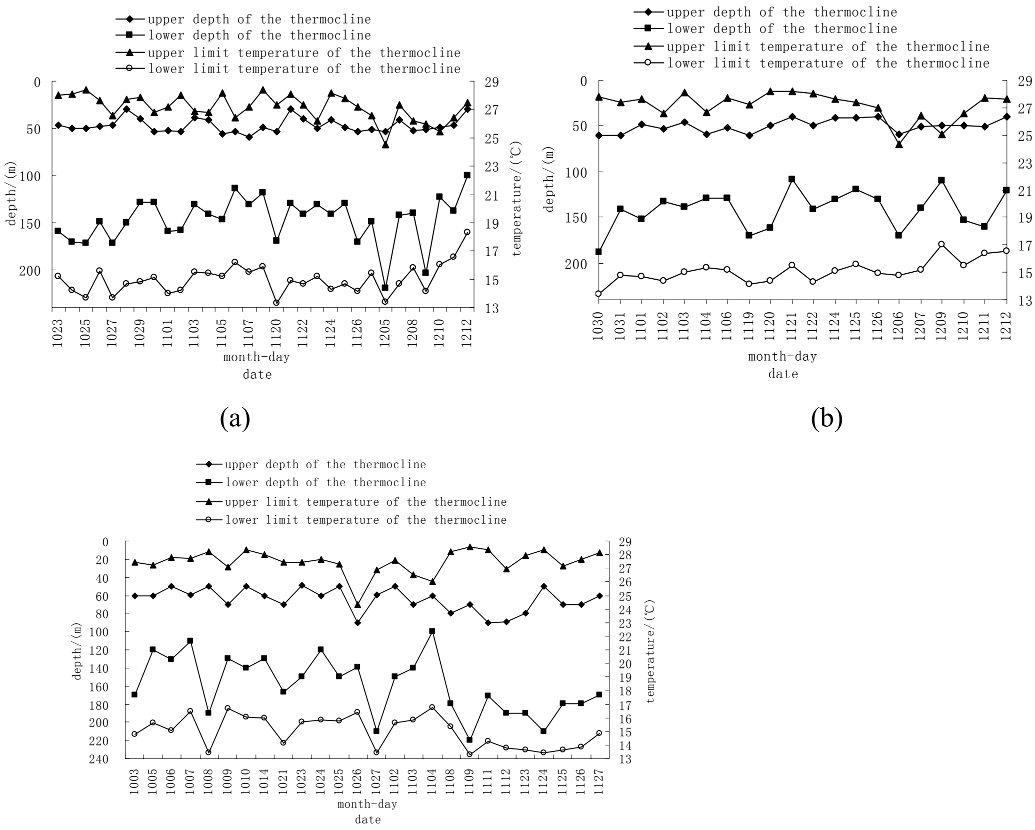
The hooked individuals of bigeye tuna in water layers (denoted as N_l) were calculated according to the hook code in which the fish was hooked (Song et al.,2006). Bigeye tuna's catch rates (denoted as R_l) in varied water layers l were calculated as :

$$R_l = \frac{N_l}{f_l} \times 1000 \tag{14}$$

Differences in the catch rate of bigeye tuna at and below the thermocline were evaluated using the t-Test (paired two samples for means).

3 Results

The upper and lower depth of the thermocline and the corresponding temperature of *HY18, HY19* and *YY168* are shown in Fig.3a,b,c. The parameters of the thermocline of *HY18, HY19* and *YY168*, e.g. depth and temperature range of upper and lower threshold of thermocline, average depth and temperature of upper and lower threshold of thermocline, average thickness, highest intensity, lowest intensity, average intensity and average difference between the upper and lower threshold of the thermocline, were shown in Table 1.



(a)

(b)

(c)

Fig.3 The upper and lower depth of the thermocline and the corresponding temperature of *HY18* (a), *HY19*(b), and *YY168* (c).

Bigeye tuna’s catch rates at and below the thermocline of *HY18,HY19* and *YY168* were shown in Fig. 4a,b and c. The sampling days when bigeye tuna’s catch rate below the thermocline was higher than the catch rate at the thermocline of *HY18, HY19* and *YY168* were accounted for 69.57%, 100% and 62.50%, respectively. For *HY18, HY19* and *YY168*, number of hooks catching bigeye tuna, individuals of caught bigeye tuna (hook code recorded) and bigeye tuna's catch rates at and below the thermocline were shown in Table 2.

The results of t-test paired two samples for means analysis about catch rates of bigeye tuna at and below the thermocline were shown in Table3. When P=0.05, by two-tailed test, the catch rates of bigeye tuna at and below the thermocline had no significant difference (P=0.07>0.05, 2005; P=0.35>0.05, 2006).

Tab. 1　Parameters of the thermocline of *HY18* ,*HY19* and *YY168*

parameters of the thermocline		***HY18***	***HY19***	***YY168***
upper limit of thermocline	depth range(m)	29.4-59.5	39.7-60.8	30.2-89.9
	temperature range(℃)	24.5-28.4	24.3-28.2	24.3-28.6
	average depth(m)	47.1	50.0	61.8
	average temperature(℃)	27.2	27.2	27.6
lower limit of thermocline	depth range(m)	100.2-219.3	109.1-188.4	99.9-240.4
	temperature range(℃)	13.3-18.3	13.4-17.0	13.1-16.7
	average depth(m)	146.9	141.2	162.1
	average temperature(℃)	15.0	15.1	14.9
average thickness of the thermocline (m)		99.8	91.1	100.3
highest intensity of the thermocline (℃.m^{-1})		-0.181	-0.183	-0.234
lowest intensity of the thermocline (℃.m^{-1})		-0.067	-0.086	-0.077
average intensity of the thermocline (℃.m^{-1})		-0.127	-0.136	-0.139
average difference between the upper and lower limit of the thermocline (℃)		12.2	12.1	12.7

Tab. 2　Average catch rate of bigeye tuna of *HY18* ，*HY18* and *YY168*

at and below the thermocline　(inds.per 1000hooks)

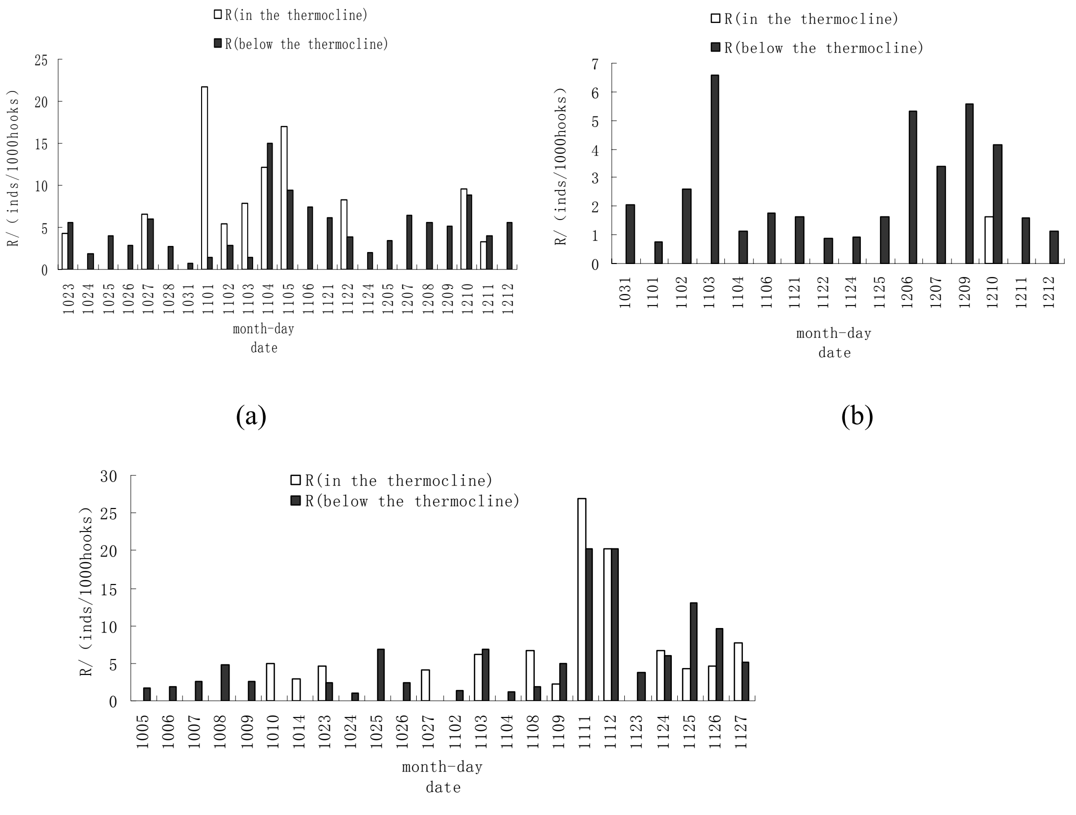
		HY18	*HY19*	Pooled data **of** *HY18,HY19*	*YY168*
in the thermocline	number of hooks	5380	5496	10876	8503
	inds. of caught fish (hook code recorded)	18	1	19	52
	average catch rate	4.18	0.10	2.14	4.27
below the thermocline	number of hooks	29880	23104	52984	21949
	inds. of caught fish (hook code recorded)	146	66	212	123
	average catch rate	4.88	2.57	4.28	5.02

Tab.3　The result of t-test paired two samples for means analysis

about catch rates of bigeye tuna at and below the thermocline

	HY18,HY19		*YY168*	
	R(in the thermocline)	R(below the thermocline)	R(in the thermocline)	R(below the thermocline)
average	2.51	3.93	4.27	5.02
variance	26.05	8.73	43.76	31.92
observations	39	39	24	24
df	38		23	
t Stat	-1.84		-0.95	
P(T<=t)Two-tailed	0.07		0.35	

Note: R means catch rate



(a) (b)

(c)

Fig.4 Bigeye tuna’s catch rates at and below the thermocline of *HY18(a)*，*HY19(b)* and *YY168 (c)*

4 Discussions

4.1 The further investigation on the mixed layer are required whether there is no distribution of bigeye tuna

The mixed layer average depth was about 47.1m, 50.0m and 61.8m in all available sampling days of *HY18, HY19* and *YY168*. The hook depths deployed were mostly deeper than 70m. The number of hooks at the mixed layer was very few. The record shown that there was no bigeye tuna hooked at the mixed layer because there was no hook deployed at the mixed layer on most sampling days. It was difficult to say that there was no distribution of bigeye tuna at the mixed layer, so the further investigation is required.

4.2 Bigeye tuna’s catch rate is higher below the thermocline

Using clustering analysis, the depth and temperature range of the bigeye tuna closely correlated to catch rate was 160.0～219.9m, 13.0～15.9℃ in the tropical high seas of the Indian Ocean. The depth and temperature range of the bigeye tuna more closely correlated to catch rate was 160.0～179.9m, 14.0～14.9□(Song et.al.,2006). All of them were under the average depth and temperature of the thermocline’s lower threshold in Tab.1. The water layer more closely correlated to bigeye tuna’s catch rate was below the thermocline, and bigeye’s catch rate was higher below the thermocline.

Bigeye tuna were distributed in water with the optimum temperature in a range of 10□～16□ in the Indian Ocean (Mohri and Nishida, 1999), which was in the thermocline’s lower depth or close to it, major distribution layers were extended from the water depth of 161m to 280m. Mohri and Nishida (1999) analyzed the relationship between the bigeye tuna’s vertical distribution of the Indian Ocean and the water depth and temperature. They suggested the highest catch rate was occurred in 261～280m and 11～13℃. The optimum temperature range and depth range were below the thermocline, for this reason, it was suggested that bigeye tuna’s catch rate was higher below the thermocline.

Bigeye tuna remained in the uniformed temperature surface layer at night and could descend to greater than 500 m depth at dawn, this depth was under the thermocline, which was same as the result of our suggestion. They thus mirror the vertical migrations of the small nektonic organisms of the deep sound scattering layer and extensively exploit these as a food resource (Brill et al.,2005). Acoustic tracking studies indicated that bigeye tuna display W-shaped vertical movement patterns during the day when not associated with floating objects. Bigeye tuna appeared to follow the diel vertical movements of the deep sound scattering layer (SSL) organisms and thus to exploit them effectively as a prey resource (Brill et al., 2005).

One bigeye would descend below the thermocline and then return to the mixed layer, ostensibly to warm muscles, at about 50 min intervals (Musyl et al.,2003). It was suggested that bigeye tuna dived into the deep water because of the food needs, however, due to their physical ability was limited in the deep-water areas with low temperature, they must rise to a higher temperature at the shallow area to enhance their muscle temperature, and then dived feeding again (Musyl et al.,2003).

Pooled the catch rate data of the two boats in 2005, by two-tailed test, the catch rate of bigeye tuna at and below the thermocline has no significant difference. For *YY168* in 2006, the catch rate had no significant difference either. Bigeye tuna’s catch rates were observed to increase continuously from first depths of encounters to the bottom of the lines, or to wherever available oxygen levels fell below 1ml.L^{-1}, whichever came first (Sharp,2001). We suggested that from the surface mixed layer to the thermocline, then to the deep water layer that was the maximum depth of longline reached (<500m), bigeye tuna's catch rates gradually increased. But the catch rate of bigeye tuna at and below the thermocline had no significant difference.

4.3 Why did the catch rates of bigeye tuna at and below the thermocline have no significant difference ?

Bigeye tuna had a unique function that while binding oxygen to hemoglobin in the low-oxygen environment, blood could also carry oxygen to all the organs of the body at the same time, bigeye's blood transporting capacity was stronger than skipjack and yellowfin tuna (Lowe et al.,2000).

Bigeye tuna had ability to adapt to the dramatic changes in the temperature of the environment, and a wider range of vertical movement, so they could feed in deeper water depth. In this sampling area, we suggested that the average temperature difference between the upper and lower threshold of thermocline was about 12.1,12.2 and 12.7℃. Adult bigeye tuna could suffer dramatic changes in the temperature of 20℃ in a short period (Brill et al.,2005). So bigeye tuna could swim across the thermocline, and feed under it. That might be the reasons why the catch rate of bigeye tuna at and below the thermocline had no significant difference.

4.4 Outlook

The results of this paper were limited to this sampling area, for the other waters, yet to be validated. The thermocline depth, thickness and intensity and other conditions of the marine environment were different in different waters. Factors impacting tuna vertical distribution and their behavior were more complex. Sampled area and times of 3 vessels were limited, the data collected were also limited. The sampling data should be collected extensively. Meanwhile collecting sampling data in the same area for one year or several years to analyze, the results would be more reliable.

Acknowledgement

We thank the general manager Fang Jingmin, vice general manager Huang Fuxiong and Fu Fachun, senior engineer Zheng Zhongxin of Guangyuang Fishery group Ltd of Guang Dong province for their supporting to this project. We also thank the managers Liu Jianru, Zhang Hua and Wang Shigang, senior engineer Zhang Ningbo, the assistant engineer Xu Shuo, the captain and crews of tuna longliner *HY18,HY19* and *YY168* of the Fishing company of Guangyuang Fishery Group Ltd of Guangdong province and the graduate students of Shanghai Fishery University Jian Wenxin, Wang Jiaqiao, Gao Panfeng and Zhou Ji for their assistances and data collection during the experiment.

Reference

Bach P, Dagorn L, Josse E,et al. Experimental research and fish aggregating devices (FADs) in French Polynesia. SPC FAD Inf Bull, 1998, 3: 3–19.

Bach P, Wendling B, Abbes R, et al. Characteristics of albacore (*Thunnus alalunga*) catches achieved by experimental fishing using instrumented longline in the French polynesian exclusive economic zone (EEZ). In: Proceedings of the Sixth South Pacific Albacore Research Workshop on WP 15. Cook Islands, March 5–7, 1996: 10.

Bertrand A, Josse E, Bach P, et al.. Hydrological and trophic characteristics of tuna habitat: consequences on tuna distribution and longline catchability. Can J Fish Aquat Sci, 2002, 59: 1002–1013.

Bertrand A, Josse E, Masse´ J. *In situ* acoustic target-strength measurement of bigeye (*Thunnus obesus*) and yellowfin tuna (*Thunnus albacares*) by coupling split-beam echosounder observations and sonic tracking. ICES Journal of Marine Science, 1999, 56: 51–60.

Boggs C H. Depth, capture time, and hooked longevity of longline-caught pelagic fish: timing bites of fish with chips. Fish Bull US, 1992, 90: 642–658.

Brill R W, Block B A, Boggs C H, et al. Horizontal movements and depth distribution of large adult yellowfin tuna (*Thunnus albacares*) near the Hawaiian Islands, recorded using ultrasonic telemetry: implications for the physiological ecology of pelagic fishes. Marine Biology ,1999, 133 : 395-408.

Brill R W, Bigelow K A, Musyl M K, et al. Bigeye tuna(*Thunnus obesus*) behavior and physiology and their relevance to stock assessments and fishery biology. Col Vol Sci Pap, ICCAT, 2005, 57, (2): 142-161.

Bureau of technical supervision of the P.R of China. The specification for oceanographic survey, oceanographic survey data processing (GB/T 12763.7—91). Standards press of China,1992,68-70.

Cayré P. Behaviour of yellowfin tuna (*Thunnus albacares*) and skipjack tuna (*Katsuwonus pelamis*) around fish aggregating devices (FADs) in the Comoros Islands as determined by ultrasonic tagging. Aquat Living Resour, 1991, 4:1–12.

Cayré P, Marsac F. Modelling the yellowfin tuna (*Thunnus albacares*) vertical distribution using sonic tagging results and local environmental parameters. Aquat Living Resour,1993, 6: 1–14.

Dagorn L, Bach P, Josse E. Movement patterns of large bigeye tuna (*Thunnus obesus*) in the open ocean, determined using ultrasonic telemetry. Mar Biol, 2000, 136: 361–371.

Gunn J, Block B. Advances in acoustic, archival and satellite tagging of tunas[M]. Block, B., Stevens, E.D. (Eds.), Tuna: physiology, ecology and evolution. fish physiology series, 19. Academic Press, New York, 2001, 167–224.

Hanamoto E. Effect of oceanographic environment on bigeye tuna distribution. Bull Jpn Soc Fish Oceanogr, 1987, 51: 203–216.

Holland K N, Brill R W, Chang R K C. Horizontal and vertical movements of yellowfin and bigeye tuna associated with fish aggregating devices. Fish Bull US, 1990, 88: 493–507.

Josse E, Bach P, Dagorn L. Simultaneous observations of tuna movements and their prey by sonic tracking and acoustic surveys. Hydrobiologia, 1998, 371/372:61–69.

Kitagawa T, Kimura S, Nakata H, et al. Overview of research on tuna thermo-physiology using electric tags. Mem Natl Inst Polar Res Spec Issue, 2004,58: 69–79.

Lowe T E, Brill R W, Cousins K L. Blood oxygen-binding characteristics of bigeye tuna (*Thunnus obesus*), a high-energy-demand teleost that is tolerant of low ambient oxygen. Mar Biol, 2000, 136: 1087-1098.

Mohri M, Nishida T. Distribution of bigeye tuna and its relationship to the environmental conditions in the Indian Ocean based on the Japanese longline fisheries information . IOTC Proceedings, 1999 2: 221- 230.

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

Nishi T. The hourly variations of the depth of hooks and the hooking depth of yellowfin tuna (*Thunnus albacares*) and bigeye tuna (*Thunnus obesus*), of tuna longline in the eastern region of the Indian ocean. Mem Fac Fish, Kagoshima Univ, 1990, 39: 81–98.

Pelagic Fisheries Research Program (PFRP) Newsletter. Oceanography’s Role in Bigeye Tuna Aggregation and Vulnerability.1999, 4(3).

Saito S. On the depth of capture of bigeye tuna by further improved vertical long-line in the tropical Pacific. Bull Jpn Soc Sci Fish, 1975, 41: 831–841.

Schaefer K M, Fuller D W. Movements, behavior, and habitat selection of bigeye tuna (*Thunnus obesus*) in the eastern equatorial Pacific, ascertained through archival tags. Fish. Bull, 2002, 100:765–788.

Sharp G D. Tuna oceanography—an applied science. Barbara A Block, E Donald Stevens. Tuna physiology, ecology, and evolution. Fish Physiology Series, 19. Academic Press, San Diego, 2001, 348-351.

Song L M, Zhou J, Zhou Y Q,et al. Environmental preferences of longlining for bigeye tuna (*Thunnus obesus*) in the tropical high seas of the Indian Ocean. 2006b, IOTC-WPTT-14.

Song L M, Zhou J ,Gao P F, et al. Modeling the hook depth of the tuna longline in the tropical areas of the Indian Ocean [R]. 2007,IOTC-WPTT-13.

Suzuki Z, Kume S. Fishing efficiency of deep longline for bigeye tuna in the Atlantic as inferred from the operation in the Pacific and Indian Oceans. ICCAT Collect Vol Sci Pap, 1982, 17: 471–486.

Yamaguchi Y. Tuna long-line fishing IV: fish ecology in the context of tuna long-line fishing. Mar Behav Physiol, 1989, 15: 51–83.