Received: 28 August 2013

The capture depth of the dominant bycatch species and the relationship between their catch rates and the sea surface temperature

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Abstract: On the basis of the data collected on a pelagic longline vessel from November 18, 2012 through March 31, 2013 in the fishing area of the Indian Ocean (2°47′N～8°13′S，62°18′E～67°49′E), the capture depth of the dominant bycatch species and the relationship between their catch rates and the sea surface temperature were analyzed. The results showed that (1) blue shark (*Prionace glauca*) mainly inhabited the water layer of 80～160m, the water layer with the highest catch rate was 120～160m, followed by 80～120m, the catch rate of remaining water layers was low; (2) swordfish (*Xiphias gladius*) mainly inhabited the water layer of 80～200m, the catch rate of this water layer increased at first then decreased, the catch rate in the water layer of 120～160m was the highest and much higher than that of other water layers; (3) blue marlin (*Makaira nigricans*) was mainly caught in the water layer of 80～200m, the catch rate of this water layer was high, and the catch rate peaked in the water layer of 160～200m. The catch rate in the water layer of 200～280m was low, and decreased with depth; (4)striped marlin (*Tetrapturus audax*) was caught in the water layer of 80～200m, no striped marlin was caught in other water layer, the catch rates decreased with depth; (5) crocodile shark was caught in the water layer of 200～320m, no crocodile shark was caught in other water layer, the catch rates increased with depth; (6)the catch rates of blue shark increased with the increasing of the sea surface temperature, peaked at 30.1～30.5℃; the catch rates of swordfish and blue marlin peaked at 29.6～30℃; the catch rates of striped marlin were high at 29.6～31℃ and peaked at 30.1～30.5℃; the catch rates of crocodile shark peaked at 30.6～31℃. This study suggested that the depth of the pelagic longline hook should be deployed deeper than 160m and shallower than 280m or avoid operation in the area where the sea surface temperature is higher than 29.6℃ to reduce the bycatch of blue shark, swordfish, blue marlin and striped marlin.

Keyword: blue shark, swordfish, blue marlin, striped marlin, capture depth, sea surface temperature
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1 Introduction

Large longline vessels generally catch older age classes of bigeye tuna (*Thunnus obesus*) and bluefin tunas (*Thunnus maccoyii*[southern], *Thunnus orientalis*[Pacific] and *Thunnus thynnus*[Atlantic]) for the sashimi market and some longline fleets target albacore (*Thunnus alalunga*) for canning (Majkowski, 2007). Commercial fish harvest is often accompanied by the incidental catch or killing of non-commercial species, known as bycatch. Such non-commercial species include marine mammals, sharks, seabirds, sea turtles and other ecologically related species (Huang, 2011). Bycatch issue has attracted more attention from the international community, it causes the depletion of some protected species such as sharks, sea turtles, leads to huge ecological problems. Therefore, in order to protect biodiversity and the ecosystem, studies on reducing bycatch have important practical significance.

Many scholars extensively studied on longline bycatch issues and proposed some mitigation measures how to effectively reduce bycatch. Dai and Xu (2003) studied the resource density index of Shortfin mako (*Isurus oxyrinchus*) and blue sharks (*Prionace glauca*) and found that the CPUE calculated based on weight or individuals showed decline trend. Pierre and Norden (2006) tested the efficacy of shark liver oil in reducing the numbers of seabirds attending fishing vessels and the number of dives seabirds executed in pursuit of pilchard (*Sardinops neopilchardus*) baits, found that shark liver oil was effective in reducing both seabird numbers and dives on baits, compared to canola oil and sea water control treatments. Dietrich et al. (2008) concluded that integrated weight (IW) longlines and paired streamer lines were the core mitigation techniques and when deployed together, constitute the best management practice for seabird. Ward et al. (2008) found that catch rates of several species, including sharks, were lower on nylon than on wire leaders. By contrast, catch rates of valuable bigeye tuna (*Thunnus obesus*) were higher on nylon than on wire leaders. Jiang et al. (2009) found that the catch rate of blue shark showed a significant negative correlation with the sea surface temperature. The catch rate of blue shark was high in the region where the sea surface temperature was among 24.6~ 25.8℃. Zhuang et al. (2011) found that the bycatch of all sea turtles occurred in the water level where the depth was less than 273 m. Therefore, if the setting of shallow hook was reduced, bycatch rate of sea turtle might be reduced. In addition, fishing in the region where the bycatch rate of sea turtle was high, using ring hooks and squid bait should be avoided. The fishermen should be trained to deal with live turtles and use tools to remove the hooks. These measures could improve the survival rates of sea turtles after they were released. Song and Hu (2011) analyzed the bycatch data of blue sharks obtained from Marshall Islands waters, found that blue shark mainly inhabited the water layer of 80～120m. Cao et al. (2011) reported that the optimum swimming depth, water temperature range of bigeye thresher sharks (*Alopias superciliosus*) were identified as 240-360 m, 10-16 ℃, respectively, while for thresher sharks(*Alopias vulpinus*) they were 160-240 m, 18-20℃ during daytime. And some mitigation measures were recommended to reduce the bycatch of bigeye thresher shark and thresher shark. Tolottia et al. (2013) analyzed catch and effort data from 14,835 longline sets conducted by foreign tuna longline vessels chartered by Brazil, from 2004 to 2010. The results indicated that the use of deep longline hooks (>100 m) might reduce the bycatch of oceanic whitetip sharks (*Carcharhinus longimanus*).

In pelagic longline fisheries incident catch can be reduced by limiting the availability of baited hooks (e.g., within bycatch species' preferred depths and water temperatures) (Carruthers et al., 2011). The depth at which species are captured is fundamental to understand the impacts of longline fisheries on target and bycatch species (Bigelow et al., 2006). To study the depth where bycatch species are caught, can help us understand its habitat utilization. Then we can control the hook depth, and avoid setting too many hooks in the water layers where the bycatch species mainly inhabit. It will be benefit to reducing the catch rates of bycatch species, such as sharks, billfishes and sea turtles. In addition, there is a significant relationship between sea surface temperature (SST) and catch rates of bycatch species. To study and understand the sea surface temperature when the catch rates of bycatch species are high will help us reduce the catch rates of bycatch species.

This study analyzed the preferred depth of dominant bycatch species: blue shark, swordfish (*Xiphias gladius*), blue marlin (*Makaira nigricans*), striped marlin (*Tetrapturus audax*) and the relationship between their catch rates and sea surface temperature based on the data collected from the fishing area of the Indian Ocean (2°47′N～8°13′S, 62°18′E～67°49′E). This study will provide a practical reference for reducing bycatch in the pelagic longline fishery.

2 Materials and methods

2.1 Materials

The survey vessel was the pelagic longline fishing vessel "Xinshiji No. 85", the main particulars of the vessel were as follows: lengthover all 56.50m; molded breadth 8.50m; moulded depth 3.65m; engine power 735.00kW; maximum speed 11.5kn.

The sampling duration was from November 18th, 2012 through March 31th, 2013. The sampling area was defined as 2°47′N～8°13′S, 62°18′E～67°49′E (Fig.1).

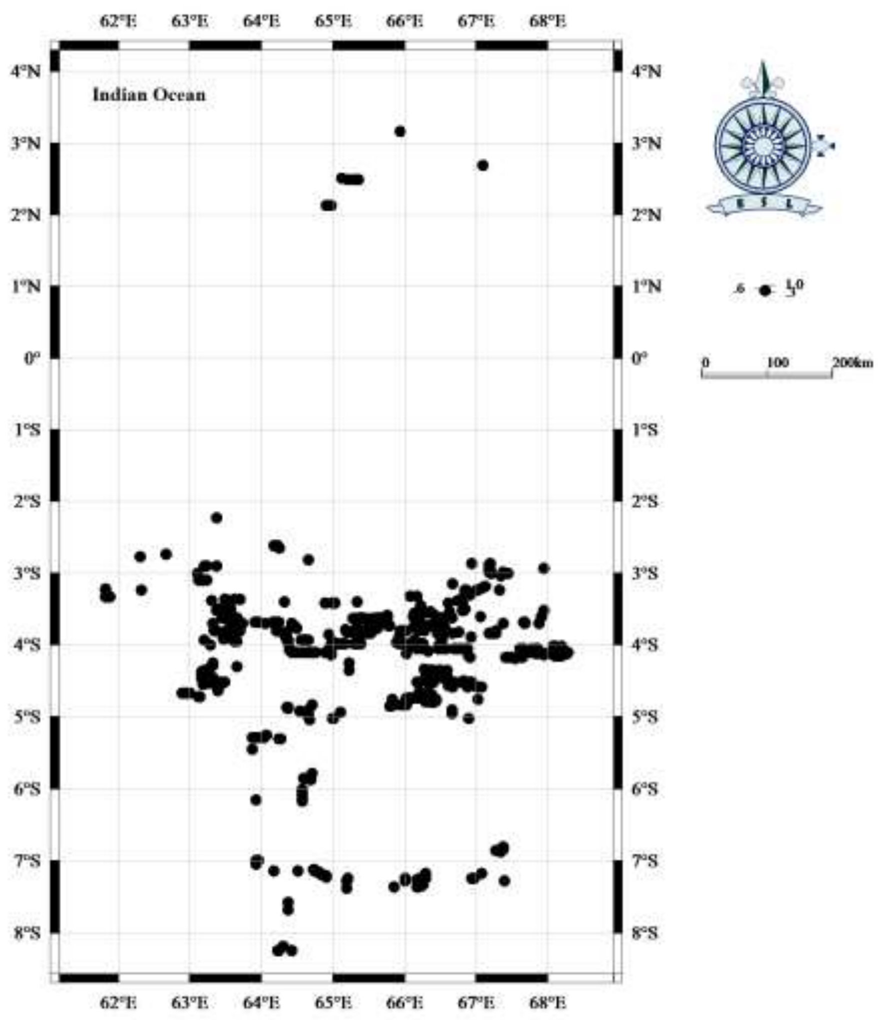

Fig. 1 Survey area and sites

2.2 Fishing gear and methods

The longline gear consisted of a 360 mm diameter hard plastic floats, 4.5 mm diameter nylon float line and 35m length, 6.5 mm diameter multifilament main line. The first section of the branch line was made of polyester and was 2.0 m long. The second section was made of nylon monofilament and its diameter was 2.5 mm, 19m long. The third section was made of 3.0 m long and 2.5 mm diameter rope centered in lead. The forth section was made of nylon monofilament, 2.0 mm diameter, and 13m long. The fifth section was made of 3.0 m long and 2.5 mm diameter rope centered in lead. The sixth section was made of nylon monofilament, 1.3 mm diameter, and 8m long. There were two parts in the first section, connected with a leaden barrel swivel. One section and another section were connected with a swivel. The sixth section connected with hooks directly. The overall length of branch line was about 48 m. We used two kinds of fishing gear in this study. The conventional fishing gear and experimental fishing gear. Conventional gear was used as a control group without message weight. The configuration of conventional fishing gear between two floats was shown in Fig. 2. There were 16 hooks between two successive floats. We used 2kg, 3kg, 4kg and 5kg messenger weight in the experimental gear and the messenger weight were placed in the main line below the float. Experimental gears were deployed at the beginning position of the whole fishing gears. The configuration of experimental fishing gear between two floats was shown in Fig. 3. There were 16 hooks between two successive floats.

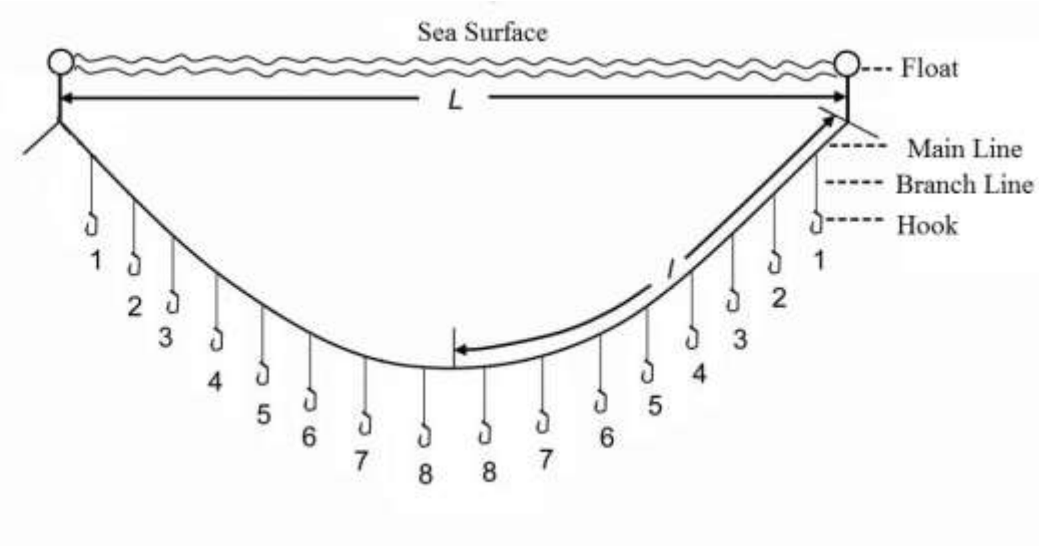

Fig.2 The configuration of conventional fishing gear between two floats

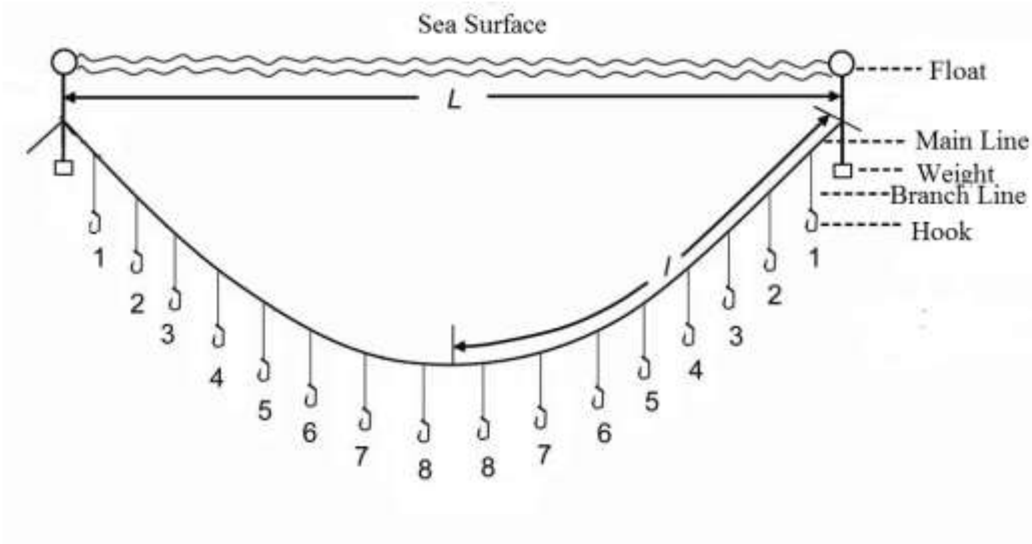

Fig. 3 The configuration of experimental fishing gear between two floats

In general, the gear deployment occurred from 06:00 to 11:30 local time, lasted for about 5.5 hrs. The gear was retrieved from 13:00 to 04:00 (before dawn of next day), lasting for 15 hours. In the operation, the vessel speed was about 10.1kn, and line shooter speed was about 6.7m s^{-1}. The time interval between deploying the fore and after branch lines was 7.4 s. There were 16 hooks between two floats. The total hooks per set ranged from 1424 to 3504 hooks.

During the investigation, the following operational data were also collected: deployment position and time, course and speed, time of retrieving lines, number of hooks per set, position and time of retrieving lines, number of hooked blue shark, swordfish, blue marlin and striped marlin per day, the code of hook with which the fishes were caught, the hooked position and time of fishes.

2.3 Instrumentation and methods

The hook depth and the sinking rate were measured and recorded by ten DRs (DR-1050, RBR Co., Ottawa, Canada). The depth measurement error of DRs was within ±0.05 % in depths of 10-740 m. Taking into account the accuracies of data from the instrument and requirement of the study, the data of depth was processed to one effective decimal place.

While deploying the longline, DRs were attached to connecting points between the mainline and the branch line for various no. of branch lines. The branch line was replaced by the rope of DR. In the end, the depth of every hook position was measured by these DRs. The length and material of the ropes which were used to connect the DRs were same as that of the branch lines.

2.4 **Data analysis methods**

Based on the operation parameters and theoretical hook depth (D_T), the calculation model of the hook depth was built by the multiple linear regression method used *R* software.

The theoretical hook depth of conventional gear was calculated by the catenary curve equation (Saito, 1992) written as:

$$D_T = h_a + h_b + l\left[\sqrt{1+\cot^2\varphi_0} - \sqrt{\left(1-\frac{2\Psi}{M_k}\right)^2 + \cot^2\varphi_0}\right] \quad (1)$$

$$L = V_2 \times M_k \times \Delta t \quad (2)$$

$$l = {V_1 \times M_k \times \Delta t}/{2} \quad (3)$$

$$\tau = {L}/{2l} = {V_2}/{V_1} = \cot\varphi_0 sh^{-1}(\mathrm{tg}\varphi_0) \quad (4)$$

where D_T , h_a , h_b , l were theoretical hook depth, branch line length, float line length, half of the main line length, respectively. φ_0 was the angle between the horizontal line and the tangent of the connecting position of the float line and mainline and was calculated by sag ratio because it was difficult to be measured in the field. Ψ was hook number ($\Psi = 1, 2, ..., 8$). M_k was the subsection number of the main line between two successive floats, that was the number of branch line plus 1. L was the sea surface distance between two successive floats. V_1 and V_2 were the line shooting speed (m s^{-1}) and vessel speed (m s^{-1}). Δt was the time interval of two successive branch lines deployed.

For the conventional fishing gear, the hook depth was affected by the drift speed of fishing gear (V_g), wind speed (V_w), leeway and drift angle (γ), wind angle ($\sin Q_w$) and hook number (Ψ). For the experimental fishing gear, the hook depth was affected by the weight of messenger weight (W) in addition to the factors affecting the hook depth of conventional gear. We took the logarithm of these parameters as independent variables, the logarithm of the ratio of the actual hook depth (measured by DR) with the theoretical hook depth as the dependent variables. We input these data into R software for regression, and got the formula of hook depth ratio. We could estimate the hook depth (prediction hook deep) based on these parameters. The drift speed of fishing gear was the speed over ground of fishing gear by the force of wind and current; wind speed was measured by wind velocity indicator; leeway and drift angle was the angle between drift direction of fishing gear and ship's heading when the gear was deployed; wind angle was the angle between wind direction and ship's heading when the gear was deployed; messenger weight was the weight (in water) of cement blocks which were placed in main line.

For the conventional fishing gear, the hook depth was mainly affected by hook number (Ψ), drift speed of fishing gear (V_g), and leeway and drift angle (γ). The calculation formula for prediction hook depth of conventional gear was:

$$\overline{\mathrm{D}} = \mathrm{D_T} \cdot 10^{0.0066\text{-}0.058\lg(\psi)\text{-}0.042\lg(\mathrm{V_g})+0.0023\lg(\sin\gamma)} \qquad (5)$$

For the experimental fishing gear, the hook depth was mainly affected by hook number (Ψ), leeway and drift angle (γ) and wind angle ($\sin Q_w$). The calculation formula for prediction hook depth of experimental gear was:

$$\overline{\mathrm{D}} = \mathrm{D_T} \cdot 10^{0.11\text{-}0.12\lg(\psi)+0.0062\lg(\sin\gamma)+0.15\lg(\sin\mathrm{Q}_w)} \qquad (6)$$

3 **RESULTS**

3.1 Composition of dominant bycatch

During the survey, we caught and identified 57 sharks. There were 21 crocodile sharks (*Pseudocarcharias kamoharai*), 14 blue sharks, 12 shortfin makoes, five silky sharks (*Carcharhinus falciformis*), four bigeye thresher sharks, and one scalloped hammerhead shark (*Sphyrnalewini*). In addition, we caught 145 swordfishes, and recorded the code of hook with which 34 of them were caught. We caught 99 blue marlins, and recorded the code of hook with which 28 of them were caught. We caught 26 striped marlins and recorded the code of hook with which 11 of them were caught. This study analyzed the preferred depths and the relationship between catch rates and sea surface temperature of dominant bycatch species, e.g., blue shark, swordfish, blue marlin, striped marlin. The sampling information of blue shark, swordfish, blue marlin and striped marlin were shown in Table.1.

Table.1 The sampling information of blue shark, swordfish, blue marlin and striped marlin

Species	Latin name	Total number	The individuals which the code of hook were

			recorded
blue shark	*Prionace glauca*	14	14
swordfish	*Xiphias gladius*	145	34
blue marlin	*Makaira nigricans*	99	28
striped marlin	*Tetrapturus audax*	26	11
crocodile shark	*Pseudocarcharias kamoharai*	21	21

3.2 Water layer where the dominant bycatch species were caught

Blue shark mainly inhabited the water layer of 80～160m, the water layer with the highest catch rate was 120～160m, followed by 80～120m, the catch rates of remaining water layers were low (Fig.4).

Swordfish mainly inhabited the water layer of 80～200m, the catch rate of this water layer increased at first then decreased, the catch rate in the water layer of 120～160m was the highest and much higher than that of the other water layers (Fig.4).

Blue marlin was mainly caught in the water layer of 80～200m, the catch rate of this water layer was high, and the catch rate peaked in the water layer of 160～200m. The catch rate in the water layer of 200～280m was low, and decreased with depth (Fig.4).

Striped marlin was caught in the water layer of 80～200m, no striped marlin was caught in other water layer, the catch rates decreased with depth (Fig.4).

Crocodile shark was caught in the water layer of 200～320m, no crocodile shark was caught in other water layer, the catch rates increased with depth (Fig.4).

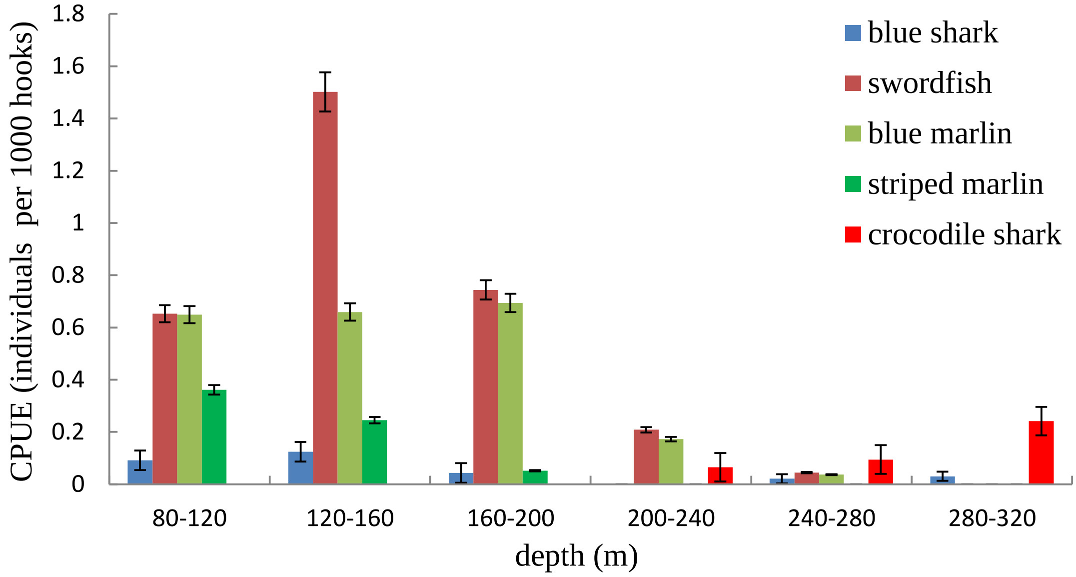

Fig.4 CPUE of each water layer where the dominant bycatch species were caught

3.3 Relationship between catch rates of dominant bycatch species and sea surface temperature

The catch rates of blue shark increased with the increasing of the sea surface temperature, peaked at 30.1～30.5℃ (Fig.5).

There is no obvious relationship between catch rates of swordfish or blue marlin and sea surface temperature, and the catch rates of swordfish and blue marlin peaked at 29.6～30℃ (Fig.5).

The catch rates of striped marlin were high at 29.6～31℃ and peaked at 30.1～30.5℃ (Fig.5).

The catch rates of crocodile shark decreased with the increasing of depth at first, bottomed at 29.6～30℃.Then the catch rates increased with depth. The catch rate was very high at 30.6～31℃.

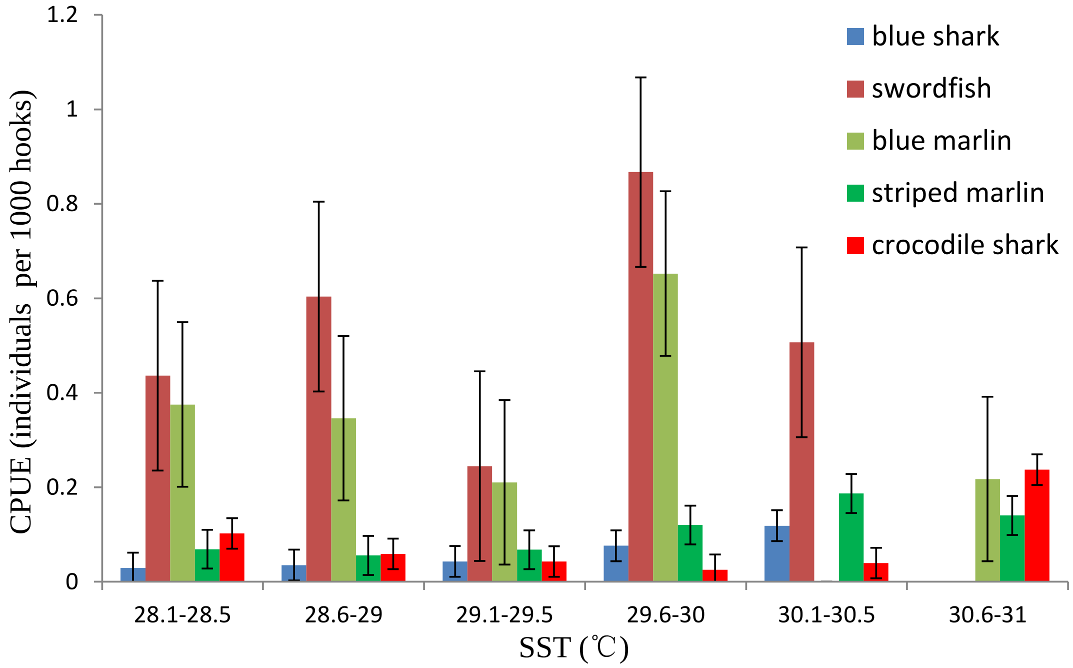

Fig.5 Relationship between catch rates of dominant bycatch species and sea surface temperature

4 DISCUSSION

4.1The inhabited water layer of the dominant bycatch species

The blue shark mainly inhabited the water layer of 80～160m in the equatorial regions of Indian Ocean. Stevens et al. (2010) used satellite telemetry to study the movements and behaviour of ten blue sharks and found that blue sharks spent between 35% and 58% of their time in depths of less than 50 m, between 52% and 78% of their time in less than 100 m and between 10% and 16% in depths greater than 300 m and showed clear diel behaviour generally occupying shallower depths at night than during the day. Song and Hu (2011) found that blue shark in waters near Marshall Islands mainly inhabited the water layer of 80～120m, basically in the thermocline of 18～28℃. There were some differences between their result and this study. This might be the individuals of recorded blue shark were small in this study. Xu et al. (2012) concluded that the average depths where the blue sharks were caught were about 194～220m. The reason for the differences between their study and this study might be the big difference in calculation of the hook depth. Xu et al.(2012) assumed that the hook depths were 75％, 80％ and 85％ of the theoretical hook depths.

The swordfish mainly inhabited the water layer of 80～200m in the equatorial regions of

Indian Ocean. Bigelow et al. (1999) observed a pronounced peak in catches in shallower waters, although catches at deeper waters were not insignificant. The latter has been attributed to the fact that the Hawaii-based swordfish fishery primarily fishes in a pelagic habitat. Sepulveda et al. (2010) concluded that all swordfish displayed diurnal vertical movements. Collectively, the average daytime depth was 273±11m and the average night depth was 31± 5m. Han et al. (2012) studied the depths where swordfishes were caught in the central Atlantic Ocean and found that the depths were from 124.6m to 280.5m. The proportion of swordfish in the total catch showed significant change with the increasing of the depths, peaked in the water layer of 220～250m, then obviously decreased with the increasing of the depths. The differences between their result and this study, might be caused by the big hook depth difference and different surveys area.

The blue marlin was mainly caught in the water layer of 80～200m in the equatorial regions of Indian Ocean. There is the bias to study the inhabited water layer of blue marlin by using the pelagic longline because there was no hooks in the water layer of 0～80m in this study. The other scholars have studied the catch rates of blue marlin in the water layer of 0～80m. Block et al. (1992) used multiplex acoustic transmitters to monitor the depth, swimming speeds, body temperature and water temperature preference of six blue marlins and found that the blue marlin remained in the top 200 m of the water column, spending half the time in the upper 10 m, and rarely ventured below the thermocline. Yokawa and Saito (2006) found that the highest CPUE was observed in the water layer of 25-50m for blue marlin, and blue marlin remained most of its time in surface or sub-surface layers. Xu et al. (2012) concluded that the average depths where the blue marlins were caught by pelagic longline were about 188～213m. Their result was similar to this study that the catch rates of blue marlin peaked in the water layer of 160～200m.

The striped marlin was caught in the water layer of 80～200m in the equatorial regions of Indian Ocean. There is the bias to study the inhabited water layer of striped marlin by using the pelagic longline because there was no hooks in the water layer of 0～80m in this study. Brill et al. (1993) found that like Indo-Pacific blue marlin, striped marlin near Hawaii spent more than 85% of their time in the mixed layer (i.e., above 90 m depth). And the maximum depth for striped marlin appeared to be limited by water temperatures 8℃. Sippel et al. (2007) studied six striped marlins with pop-off satellite archival tags, and concluded that striped marlin spent 80%±2% of their time in the mixed layer including 72%±2% of their time in the top 5m. We found that striped marlin was caught in the water layer of 80m～200m, no striped marlin was caught in other water layers, the catch rates decreased with depth.

Until 2 July 1987, crocodile shark had not been reported from the equatorial part of the Indian Ocean. A specimen of crocodile shark was caught in a pelagic tuna net at 3° 22′ S and 62° 18′ E at a depth between 72 and 211 m (Romanov and Zamorov,1994). Crocodile shark inhabited from the ocean surface to at least 590 m depth (Last and Stevens, 1994). Xu et al. (2012) concluded that the average depths where the crocodile sharks were caught by pelagic longline were about 169～191m.There are few studies about the inhabited water layer of crocodile shark, in the future, we should do more research on it.

This study suggested that the depth of the pelagic longline hook should be deployed deeper than 160m to reduce the bycatch of blue shark, swordfish, blue marlin and striped marlin and deployed shallower than 280m to reduce the bycatch of crocodile shark.

4.2 The relationship between catch rates of the dominant bycatch species and sea surface temperature

The catch rates of blue shark increased with the increasing of the sea surface temperature, peaked at 30.1～30.5℃ in the equatorial regions of Indian Ocean. The preferred sea surface temperature (SST) for blue shark was different from the season and sea area. Vas (1990) found that short-term fluctuations in SST were found to be responsible for changes in the distribution of the population of blue sharks. Hazin et al. (1994) concluded that seasonal fluctuation of catch per unit of effort (CPUE) as related to sea surface temperature. During 1990, in general, the CPUE of males tended to decrease with an increase in the sea surface temperature, whereas the CPUE of females tended to increase. But Stevens et al. (2010) used satellite telemetry to study the movements and behaviour of ten blue sharks off eastern Australia, and found that there was no overall preference for SST shown by the four sharks in ten. Mean SST values experienced by the four sharks were 20.3°C, 24.0°C,18.7°C and 15.7°C, respectively. The survey area of this study was in equatorial regions, so the SST was high and minimum temperature was 28.1℃. We found that the catch rates of blue shark increased with the increasing of the sea surface temperature, peaked at 30.1～30.5℃. And the catch rates increased slowly at 28.0～29.5℃, increased rapidly at 29.6～30.5℃.

The catch rates of swordfish peaked at 29.6～30℃ in the equatorial regions of Indian Ocean.

The preferred SST for swordfish was different from the season and sea area. Damalas et al. (2007) showed that the Generalized additive models (GAM) plot of catches in response to sea surface temperature (SST) detected two temperature intervals (16～18℃ and >26℃) where swordfish were more frequently caught. Tserpes et al. (2008) found that the maximum catch rate of swordfish was around 22.5℃.

The catch rates of blue marlin peaked at 29.6～30℃ in the equatorial regions of Indian Ocean. The preferred SST for blue marlin was different from the season and sea area. Block et al. (1992) found that blue marlin showed a similar preference for the warm mixed layer. They inhabited the waters where the water temperature ranged between 17℃ and 27℃. Su et al. (2008) concluded that SST accounted for more than 60% of the explained deviance in the four models and leaving SST out of the model led to the greatest change in deviance.

The catch rates of striped marlin were high at 29.6～31℃ and peaked at 30.1～30.5℃ in the equatorial regions of Indian Ocean. The preferred SST for striped marlin was different from the season and sea area. Ortega-Garcia et al. (2008) found that SST influenced CPUE of striped marlin positively. SST had little effect on the CPUE when the SST was less than 26℃, and affected the CPUE positively when the SST was more than 26℃. Lien et al. (2012) concluded that SST explained the largest proportion of the deviance, and is therefore considered the best predictor for the habitat of striped marlin. The preferred habitat characteristics of striped marlin in high density areas were identified as SST between 23 and 26 °C.

This study suggested that the pelagic longline operation should be avoided in the area where the sea surface temperature is higher than 29.6℃ to reduce the bycatch of blue shark, swordfish, blue marlin, striped marlin and crocodile shark.

4.3 Outlook

There are limitations in predicting the spatial distribution of fish from fisheries data alone. Fisheries data may cover only limited habitats because of the limitations on the depths to which the hooks can be deployed, temporal scales, and areas covered by the fishery. Thus future surveys should include data covering wide ranges of depth, time, and area to better understand the spatial distribution of dominant bycatch species (Song and Zhou, 2010).

Acknowledgements

The project is funded by the National High Technology Research, Development Program of China (Project No. 2012AA092302), Specialized research fund for the doctoral program of higher education (No.20113104110004), and the Shanghai Municipal Education Commission Innovation Project (Project No. 12ZZ168). We thank the general manager Yuexiang Zeng, vice general manager Daochang Zheng and the crews of longliners of Zhejiang Ocean Family CO., Ltd for their supporting to this project.

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