DISTRIBUTION OF BIGEYE TUNA AND ITS RELATIONSHIP TO THE ENVIRONMENTAL CONDITIONS IN THE INDIAN OCEAN BASED ON THE JAPANESE LONGLINE FISHERIES INFORMATION

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In this report, the significant oceanographic factors influencing spatial-distributions for bigeye tuna species in the Indian Ocean were investigated on the basis of the data collected and accumulated in the past years. The results show that bigeye tuna are distributed in water with the optimum temperature in a range of 10?C-16?C irrespective of their sexual maturity and water mass. Accordingly, the vertical distribution of tuna is predicted by the temperature profile; the tunas are only found in the deeper layer in the tropical region while they are distributed up to the shallower layer in the middle latitude.On the other hand, the bigeye tuna reaching the maturity is found only beneath the layer between 0 and 50m where the sea water temperature exceeds 26?C. The size of fishing ground in the tropical region decreases during the period between June and September. This decrease coincides with the decrease in sea area where the water temperature in the layer above 50m is warmer than 26?C During this period, however, the size of the fishing ground in the middle latitude increases. Accordingly, the bigeye tunas in the middle latitude are younger and in the growing stage while those reaching maturity are dominate in the tropical region, and this bigeye tuna distribution is dependent on the vertical temperature profile of each sea area.

INTRODUCTION

Tuna longline fishing by Japan in the Indian Ocean started in 1952 in the area south of Java Island and was expanded both westward and southward, covering the entire area north of 50?S in 1968 (Hirayama, 1989). Despite this fact, there exist small amount of studies and reports concerning line fishing of bigeye tuna in the Indian Ocean as compared with the Pacific. Bigeye tuna, which engages in an extensive north-south migration, has a wide distribution area throughout the Indian Ocean (Kume *et al*., 1971). Data and materials obtained through Japanese tuna longline fishing are effective both in quantity and quality in exploring spatio-temporal distribution and their factors as they cover longer periods and areas as compared with those collected by other countries (Republic of Korea and Taiwan). On the other hand, there are some factors that make a fishing ground to be eligible for fishing operation. By clarifying those factors, it would be possible to contribute to effective exploration of fishing ground and promotion of the optimum conservation and management of the resources.

As factors of distribution of bigeye tuna, one can enumerate, beside the internal factors of maturity, such external factors as water temperature, dissolved oxygen amount, salinity, light, sea currents and sea-bottom shape. Although there are numerous such factors, it is considered that fishes are affected by single environmental factors or their combinations. Further, it can be assumed that even the same factors may have different effects in the growth and maturity stages of bigeye tuna. For this reason, it is necessary to fully grasp which factors affect bigeye tuna. As the distribution of bigeye tuna is extensive, accumulation of data and materials extensively covering distribution areas is needed among aforementioned factors. Furthermore, changes of factors by area should be clear as numerical value. In other words, it is necessary that they serve as quantitative indexes for distribution factors. Therefore, three factors: water temperature, dissolved oxygen amount, maturity stages of bigeye tuna were considered for the entire Indian Ocean and for each area taking the above points into consideration. Salinity density is considered as other factors, but the amount of change in salinity was not treated as the major factors because it is reported that it is relatively small in the outer waters (Ishino, 1991). In the present study, spatio-temporal distribution of fishing areas through available long-term data and materials were obtained concerning bigeye tuna in the Indian Ocean.

Next, the following analyses were made to know distribution factors:

- distribution of mature bigeye tuna fishing areas by sea area the optimum fishing temperature of
- bigeye tuna, characteristic of water temperature desired for
- mature bigeye tuna to be distributed, and the minimum dissolved oxygen amount versus the
- minimum dissolved oxygen amount characteristics of the distribution by area of the optimum fishing temperature of bigeye tuna
- and the minimum dissolved oxygen amount as against fishing

DATA AND MATERIALS AND ANALYSIS METHOD

Data and materials used in the present study were as follows. The author boarded the training vessel Koyo-maru in October, 1986 - January 1987, and recorded daily locations by fishing operation, the amount of fishing amount, size of caught fishes and measurement the actual depth of hooks. He also conducted marine observations using Nanzen water-collecting device before line retrieval, and measured weight of ovaries fork length after line retrieval and collected data and materials. Besides, the following available data and materials were used for entire Indian Ocean.

Horizontal distribution of fishing

In order to obtain horizontal distribution of number of fishes caught, "Report on the results of statistical research of tuna longline fishing by fishing ground" (*) for 1967-1991, in which data were compiled by each latitudinal and longitudinal 5-degree-square cells was used. In order to examine seasonal changes assuming each latitudinal and longitudinal 5-degree-square cell as k, monthly data files per cell-k for 25 years from 1967 were compiled. Assuming number of fishes caught per cell-k in j month of j year is Nijk, monthly average number of fishes caught Njk per cell-k can be obtained by

$$Njk = \left(\sum_{i=1}^{n} Nijk\right) / nk$$

Here nk shows the number of fishing years per cell-k.

Therefore, in the case of month j, all the data aggregated for the month j, averaged by fishing years, is the average number of fishes caught Njk of month j in cell-k.

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Research Division, Fisheries Agency (1969-1973): 293pp., 283pp., 299pp., 326pp. ,319pp.

Research and Development Division, Fisheries Agency(1974-1978) 279pp.,265pp.,267pp.,269pp.,264pp.

Research Division, Fisheries Agency (1979-1982): 235pp.,241pp.,243pp.,242pp.

Pelagic fish resource division, National Research Institute of Far Seas Fisheries, Fisheries Agency (1983-1991): 249pp.,237pp.,225pp.,232pp.,225pp., 217pp.,234pp.,238pp.,238pp.

Monthly average number of fishes caught

In order to know the state of fishing in the entire Indian Ocean, monthly average number of fishes caught (Nk) was obtained with the following formula using the monthly average number of fishes caught Njk by cell-k.

$$Nk = \left(\sum_{j=1}^{n} Njk\right) / mk$$

Here, mk indicates the number of months per cell-k.

Monthly average number of fishes caught per cell-k

Classes were established using Nk and monthly average number of fishes caught (Njk). The methods were arranged from those having higher number of fishes caught per cell-k, and were divided into four classes so that each represents a quarter of the overall number of fishes caught. The number of fished 5-degree-square cells differ by the period surveyed. For this reason, the number of cells, mentioned in the ensuing section, represent the total number of cells used at the time of analysis, including those duplicated. In terms of the monthly number of fishes caught, the number of cells was 2,314 for the distribution of monthly average number of fishes caught (Njk), and 241 cells for the distribution of monthly average number of fishes caught (Nk),

Looking at distribution of monthly average number of fishes caught (Njk), in terms of 2,314 fished cells, about 380,000 fishes, which account of three quarters of the total number of fishes caught in the distribution of number of fishes caught corresponded to 504 cells in the three top classes (about 20% of the total).

Further, distribution of monthly average number of fishes caught (Nk) shows that in terms of 241 fished cells, about 34,000 fishes which accounted for three quarters of the number of fishes caught were fished in 67 cells in the top three classes (about 30% of the total) in the distribution of number of fishes caught.

Since then, in the 5-degree-square cell belonging to the upper 3 classes, the areas with many numbers of fishes caught were termed as "high-density fishing area". Further, the areas where there are many number of fishes caught belonging to the first class were called "maximum density fishing area", and area of the fourth class were called "low-density fishing area ".

Monthly average distribution of number of fishes caught

In Chart of Njk and chart of monthly average number of fishes caught distribution Nkt, different colors are used for each class. However, the fourth class was marked by black circle, of which the cells in which the number of fishes caught is zero is marked by white circle. Especially, one cell in which there was no fishing operation was left blank.

Vertical distribution of fishing

The composition of vertical distribution of fishing tuna longline is fishing gear as shown in Fig. 1 (here 11 lines per basket), and hooks can be set at the maximum depth of 300m. The vertical distribution of fishing of bigeye tuna can be estimated indirectly through comparison of fishing rate by depth.

Data files of locations of fishing operation, the number of hooks used and number of fishes caught by branch line were made, using "catch data and materials by hooks of deep longline" obtained in the "Research on new commercial development of tuna longline fishing ground" of JAMARC for six years from 1981-1986.

With respect to the depth of hooks were obtained on the assumption that actual measurements by depth gauge and shape of longline fishing gear in the water are

KENSUI-KYOKUSEN (english ??) . Fishing rate of bigeye tuna by depth range dm can be obtained by the following formula, on the assumption that that the number of hooks used in the depth range dm at 20m interval is hid and the number of fishes caught is Cid.

$$R\ d = \sum_{i=1}^{n} Cid / \sum_{i=1}^{n} hid \times 1{,}000$$

Here n is the number of data and materials in the depth range dm.

Mature individuals

Bigeye tuna to be used as materials are caught by longline, and are mature fishes of body length of 80 cm. Supposing that weight of ovaries of female bigeye tuna out of the caught bigeye tuna is W and their fork length is L, Gonad Index can be obtained from the following formula:

$$G.I. = W/L^3 \times 10^4$$

With respect to gonad index, it was proposed that G.I.? 3.1 should be treated as mature individuals since the 1950s (Kikawa , 1953; 1957), and since then it is used as index of mature individuals of bigeye tuna. In the present study as well, G.I.? 3.1 was treated as mature individuals of bigeye tuna.

With respect to horizontal distribution of maturity, data files for each latitudinal and longitudinal 5-degree-square cell for each month and year were compiled using "fish size measurement data and materials (*)" for five years from 1981.

In the same way as stated in the foregoing, monthly average number of fishes caught of mature individuals per cell-k and average monthly number of fishes caught were obtained.

But since data and materials were of small quantities, average monthly number of fishes caught was compiled on a quarter basis (e.g. January-March), and fishing distribution of mature individuals were obtained.

Relations between fishing rate and water temperature

Vertical distribution of water temperature was obtained from the results of oceanographic observation conducted in more or less the same areas before and after longline fishing operation in the Indian Ocean.

The hook depth was obtained on the assumption that hook-setting depth is actually measured value or branch line as KENSUI-KYOKUSEN (English ??), and was compared with water temperature.

Furthermore, the number of hooks used and number of fishes caught were compiled per water temperature of 1? , and fishing rate Rt, which is the number of fishes caught per 1000 hooks, with the following formula:

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Results of measurement collected under the research guidelines for research of tuna resources by prefectural government vessels (National Research Institute on Far Seas Fisheries)" during 1952-1987 (except 1954,1955).

$$R\ t = \sum_{i=1}^{n} Cit / \sum_{i=1}^{n} hit \times 1{,}000$$

, where

hit : the number of hooks used in water temperature t? in each operation point i,

Cit : number of fishes caught in water temperature t? in each operation point i,

n : the number of data and materials in water temperature t?

Here, in the data and materials of JAMARC as mentioned previously, data files were compiled from observation results of water temperature in each stratum in the location where fishing operation took place.

Relations between fishing rate and dissolved oxygen amount

Areas in the eastern side where fishing operation and the number of data and materials is well in order were selected, and seven areas (A-G east-west direction) were established from 20°N to 15°S by 5 latitudinal degrees between 85°-90°E.

Fishing rate by depth in this established area was obtained, and comparison was made with average dissolved oxygen amount in vertical sections. Minimum dissolved oxygen amounts needed for fishing were estimated.

With respect to the dissolved oxygen amount, the depth of data and materials of each observation was obtained through proportional allotment as standard depth 0,10,20,30,50,75, 100, 125, 150, 175, 200, 250, 300, 400, 500, 600, 700, 800, and 1000m. Further, its dissolved oxygen amount was obtained through proportional allotment.

With respect to cells, 1-degree-square cell was adopted for latitude and longitude and the dissolved oxygen amount was compiled for standard depth, and further the average dissolved oxygen amount of standard depth for 1-degree-square cell were obtained.

Here the relations between fishing rate and dissolved oxygen amount of bigeye tuna in the Indian Ocean were obtained using "data and materials on oceanographic observation for each stratum" collected by the Japan Marine Data Center from 1906 to 1989, besides data and materials of JAMARC.

RESULTS AND DISCUSSION (I) : SPATIO-TEMPORAL DISTRIBUTION OF FISHING OF BIGEYE TUNA

Horizontal distribution of fishing

Distribution of monthly average number of fishes caught

Fig. 2 shows distribution of monthly average number of bigeye tuna caught (Nk). According to the figure, the area subjected to the research ranges extensively from 20? N-40? S. But in the northern Arabian Sea and most of the area south of 40?S, it is observed that the number of fishes caught was zero despite the fact that fishing operation took place there.

Further, out of 241 5-degree-square cells where fishing operation took place, in the top 10 cells, 1/4 of the total number of fishes were fished.

This shows that the range of fishing distribution of bigeye tuna is very small. The high-density fishing area defined in the foregoing, were as follows:

- western tropical zone: the southern Arabian Sea - northern Madagascar island

-eastern tropical zone: waters off Java Island centering on 10? S - area south of Sri Lanka

-waters off Fremantle centering on 30? S- high latitudinal southern area off South Africa

In this way, high-density fishing area was in the tropical zone and high latitudinal southern area. Especially, maximum density fishing area with a large number of catch was inside the high-density fishing area as distribution form, and was at 0? -10?N and 50? -70? E of southern Arabian Sea.

The phenomenon that good fishing ground in the Indian Ocean is in the tropical zone and high latitudinal southern area and the number of fishes caught is small in the mid-latitudinal area between these two areas is basically the same as for the case of the Pacific and Atlantic.

It is conjectured that the optimum fishing temperature (to be discussed later) is giving crucial effect on the choices of depth for setting hooks.

Furthermore, the following characteristics were observed in the Indian Ocean. In the Bay of Bengal and northern Arabian Sea, the number of fishes caught was small, but horizontal distribution of fishing in the tropical zone did not show a higher in the east and lower in the west pattern as in the Pacific and Atlantic, but showed a contrary trend (Fig. 2).

With respect to horizontal distribution in the mid-latitudinal area, it was low-density in the western side of the Pacific and Atlantic and high-density in the eastern side; but low-density in the entire east-west area in the Indian Ocean.

In the area south of 40 ? S of the Indian Ocean, the cells with no fishing of bigeye tuna expanded rapidly (Fig. 2), despite the fact that it is an area where many hooks were set targeting at southern bluefin tuna (Shingu, 1970; 197With respect to the three characteristics in the above, it is estimated that there exist close relations with the optimm fishing temperature to be discussed later.

Distribution of monthly average number of fishes caught

In order to grasp average fishing season, average fishing season, trend of fishing ground and seasonal migration of bigeye tuna in the Indian Ocean, distribution of monthly average number of fishes caught of the same species (Njk) were obtained and are shown in Fig. 3.

According to the figure and distribution of monthly average number of fishes caught (Nk) as shown in Fig. 2, major high-density fishing areas of bigeye tuna were the following 3 areas.

- western tropical zone (southern Arabian Sea - north of Madagascar Island)

- Eastern tropical zone (south off Java Island - east of Sri Lanka)

- High latitudinal southern area (waters off Fremantle - off Cape Town)

Western tropical zone (southern Arabian Sea - north of Madagascar Island):

In the southern Arabian Sea area north of 0 degree, as shown in Fig. 3, high-density fishing areas were formed almost throughout the year. But the range of the high-density fishing area changed seasonally, and became relatively narrow in July and August, showing a shrinking trend. In this period, there were no maximum density fishing areas.

The maximu m density fishing area appears in the southern Arabian Sea area (5? -10? N-60? -70? E) in September, and is later formed in almost the same area until December (Fig. 3). In January, the maximum density distribution area of the area off Somalia (0? -10?N, 45? -55? E) is added to this area, expanding further westward. That high-density distribution area stalled in the area from Somalia - southwest off Sri Lanka to southern Arabian Sea until March.

These high-density fishing areas were found in the adjacent areas in April, and, gradually receded and narrowed in May and onward in the west off Sri Lanka.

By contrast, in the area off Somalia, maximum density fishing areas were observed until May, and reduced from June, with virtually no high-density fishing area in July-September.

n southern Arabian Sea area, high-density fishing area, including maximum density fishing area, appeared in the waters off Eastern Africa north of Madagascar (0? -10? S-40? -50? E) in June around the same time when high-density fishing area began to shrink.

In August - September, high-density fishing area expanded eastward to 70? E. From October, this high-density fishing area shrank, but, instead, maximum density fishing area stay in the southern Arabian Sea northeast of this area from September and afterwards. In this way, high-density fishing area stays from September to June next year, with January-April having the most extensive range, while beginning to shrink in July - August. In the area off Madagascar Island, it was between June - September. No high-density fishing areas were observed in the area off Somalia in July - September.

The following interpretation may be plausible to explain the above phenomenon: The fishes subject to consideration here are mature individuals of bigeye tuna, which are distributed in large numbers in the area where there exist in which water temperature to 50m below the sea surface is 26? or over (Mohri, 1999). However, the condition that water temperature to 50m below the sea surface is 26? or over is required for spawning and subsequent raising of juveniles. The strata usually inhabited by bigeye tuna are the strata of larger water depth from 10? to 16? . Also, in the tropical zone, spawning of mature individuals takes place all the year round.

With these in mind, we would consider the following: During the summer period, because of the effect of southwestern monsoon, upwelling arises in the area centering on the area off Somalia (Sudo , 1994), and water temperature to 50m below the sea surface declines below 26 ? . For this reason, fishing rate declines throughout the area. In winter, by contrast, fishing rate is considered to turn upward because water temperature to 50m below the sea surface does not decline in the absence of any effect of upwelling.

The above is the interpretation concerning aforementioned phenomena on the basis of the present study.

The above interpretation holds for the following phenomena in the two areas as well.

EASTERN TROPICAL ZONE (JAVA ISLAND - SOUTH OF SRI LANKA):

The area south of the Java Island has been high-density fishing area for almost throughout the year but its scale shrank in the largest margin in March-June. In July, the area south of the island (5? -15? S? 110? -115? E) became maximum density fishing and then, the area and the area off Sumatra became high-density fishing area including maximum density until February.

This high-density fishing area further expanded westward to 5? -15? S in January - February, and in February, reached the most westerly point of Chagos Islands area (70? -75? E).t in March, the high-density fishing area in the area near the islands disappeared, and instead, moved northward to southeast off Sri Lanka which is located on the northern side of these islands by 2- April, and was combined with the high-density fishing area in the southern Arabian Sea area.

In this way, from July, high-density fishing area from Java Island to the area off Sumatra move westward along the 5 ? -15 ? S line from January in the next year, and from February more northward from east off Chagos Islands to southeast off Sri Lanka. Conversely, along with northward movement of this high-density fishing area, high-density fishing area shrank in March-June in eastern tropical zone as mentioned in the foregoing. (5)

High latitudinal southern area (Fremantle - off South Africa):

In the summertime of Southern Hemisphere in December-March next year, high-density fishing areas were found mainly in two points at southeastern area off South Africa and coastal area off Fremantle. High-density fishing area expanded to offshore area from April, centering on west of the area off Fremantle (30? -35? S-90? -95? E), and, as the month progressed, expanded to east-west directions centering on this area and 35? -40? S-20? -25? E, 30? -35? S-65? -75? E, 30? -35? S-105? - 110? E). High-density fishing area also expanded to Africa and Australia in June - September, covering almost entire high latitudinal southern area of the Indian Ocean, with July as peak. But from October onward, these high-density fishing areas were reduced, and by March next year, high-density fishing areas were formed only in two locations in the area of southeast of South Africa and coastal areas off Fremantle.

As in the foregoing, high-density fishing areas were found in tropical zone and high latitudinal southern area, but there were no high-density fishing area throughout the year in the mid-latitudinal area ranging to 15? -25?S, centering on 20? S between these two areas.

Fig. 4 shows, by way of simulation, the fishing season, fishing ground and migration trend of bigeye tuna in the Indian Ocean based on the results of the distribution chart of monthly average number of fishes caught (Njk) with respect to the seasonal movement of high-density fishing areas.

VERTICAL DISTRIBUTION OF FISHING

As Fig. 5 shows, points to collect data and materials to examine vertical distribution of fishing of bigeye tuna was 1,198, and number of hooks was 1,871,143, and number of fishes caught was 11,059. With respect to vertical distribution of fishing of bigeye tuna. Besides the entire Indian Ocean, distribution by area was examined to grasp regional characteristics. In establishing areas, as bigeye tuna high-density fishing areas were found in the three areas of western tropical zone (WA), eastern tropical zone (EB) and high latitudinal southern area (SD), and there was no high-density fishing area in the mid-latitudinal area (MC) extending in the east-west direction and centering on 20?S, four areas as shown in Fig. 5 were established.

With respect to collection points between 10-15?S, 15?S was set at the borders of the area as there are many fishing operations near 10?S, and these were added to the tropical zone.

western tropical zone (WA): north of 15 ? S-west of 75 ? E

eastern tropical zone (EB): north of 15? S-east of 75? E

mid-latitudinal area (MC): 15 ? -25? S

high latitudinal southern area (SD): south of 25? S

Fig. 6 shows distribution of fishing rate by hook depth 20m to examine vertical distribution of fishing of bigeye tuna in the entire Indian Ocean.

As shown in the Figure, water depth for hooks were set in an extensive area of the 61- 280m strata, and therefore vertical distribution of fishing was in the same range, and fishing rate tended to show higher rate as the depth becomes larger.

It is generally said that fishing of bigeye tuna is scarce with hooks with shallow water depth. Fishing rate in the strata from 61-80m to 141-160m was 3.0 at the highest at the 100-120m stratum. But fishing rate for depth larger than that was 7.1 at the 161-180m stratum, and 15.4 at the 261-280m, showing almost linear increase as the water depth became larger (Fig. 6). The ratio of fished bigeye tuna was 85% of the total, 161-280m strata, and 40% in the 241-280m strata. No data and materials were made available for the water depth larger than 281m, but there is a possibility of increase of fishing rate for the depth of 281m or larger judging from these vertical distribution of fishing.

For this reason, it can be assumed that major distribution strata are extended from the water depth of 161m to 280m.

It is considered from this that the strata of water temperature 10-16? where usually many bigeye tuna are found ranges from the depth of 161m to 280m. On the other hand, the distribution of fishing rate of four areas (WA, EB, MC, SD) by depth showed the following trend (Fig. 7).

Western tropical zone (WA):

Fishing rate is lower than 2.5 or lower up to the stratum of 121-140m. It increased in a rectilinear manner from 5.3 of the 141- 160m stratum to 10.3 of the 201-220m stratum, and was almost the same between 201m and 280m. In the 141-280m stratum, 92% of all the bigeye tuna were caught. Data and materials for 281m or deeper are not available, but there is a possibility that it is vertical distribution of the same type at 281m or deeper judging from increasing trend of fishing rate of bigeye tuna by depth of hooks set.

Eastern tropical zone (EB):

Fishing rate showed an increasing trend along the depth but was low at 4.9 or lower up to the 141-160m stratum. However, it increased in a rectilinear manner as depth proceeded from the 8.6 at the 161-180m stratum to 19.8 at the 261-280m stratum, At the 161-280m stratum between them, about 90% of bigeye tuna were caught. A possibility of fishing of bigeye tuna at 281m or deeper is estimated, as in western tropical zone (WA), from vertical trend in fishing of these bigeye tuna.

Mid-latitudinal area (MC):

Hooks were set in the 61- 260m strata. Fishing rate was low at 0.0-1.4, and there were no differences in fishing rate by depth.

High latitudinal southern area (SD):

Hooks were set in the 61- 260m strata. Fishing rate repeated 0.7-4.0 but the differences in fishing rate by depth were not conspicuous. The trend of vertical direction of fishing of bigeye tuna is not in the intensity of western tropical zone (WA) and eastern tropical zone (EB), but a possibility of the same kind of vertical distribution of fishing at 261m and deeper. In this way, with respect to vertical distribution of fishing of bigeye tuna in the Indian Ocean, there were no differences in fishing rate by depth in mid-latitudinal area (MC) at 15? -25? S and high latitudinal southern area (SD) south of 25? S.

RESULTS AND DISCUSSION (II) : RELATIONSHIPS BETWEEN FISHING AND ENVIRONMENTS

Relations between fishing of bigeye tuna and environmental factors

Fig. 8 shows the fishing rate of mature individuals per 5-degree-square cells in 1952-1987 (except 1954-1955) in order to determine the ratio of fishing of female mature individuals in longline operation. According to the figure, the proportion of mature individuals was high in tropical zone (WA, EB) centering on the area where monthly average number of fishes caught (Nk) was large (Fig. 2), and in high latitudinal southern area (SD), the proportion of non-mature individuals was high.

But as ratio of fishing by area can be estimated by the fact that it changes from season to season even for the tropical zone (WA, EB) where proportion of fishing of mature individuals is high. Fig. 9 shows those data on a monthly basis. The following trend was obtained when seasonal changes in fishing rate of mature individuals are combined, with respect to western tropical zone (WA), and eastern tropical zone (EB) and high latitudinal southern area (SD) where bigeye tuna form high-density fishing area (Fig. 3).

Western tropical zone (WA):

The area where mature individuals are fished from January to March is wide, but from April, its area became narrower as time progressed, and in July and August, almost no mature individuals were fished, except the area off Somalia at 0? -10? N-50? -70? E. In September and afterwards, the area where mature individuals are fished expanded in the course of time.

Eastern tropical zone (EB):

The area where there is a large proportion of mature individuals throughout the year was not so conspicuous as the area off Somalia in western tropical zone (WA). Mature individuals were extensively fished from January to March, but the area in which mature individuals were caught in April and afterwards narrowed as time progressed, showing the largest shrinkage in August. Subsequently, in the course of time, the area in which mature individuals are fished expanded westward along the line of 10°S, reaching western tropical zone in October.

High latitudinal southern area (SD):

Mature individuals were not caught throughout the year. Based on the result of analysis of mature/non-mature individuals by area, it was found that mature individuals are extensively caught in tropical zone. Therefore, the bigeye tuna in this area is assumed as a spawning school (Fig.8).

However, the proportion of fishing of mature individuals changed according to season (Fig. 9). On the other hand, high-density fishing areas centering on high latitudinal southern area (MC) were considered as feeding stock because only non-mature individuals formed it.

In western tropical zone (WA) and eastern tropical zone (EB), the range of high-density fishing area at monthly average number of fishes caught (Njk) distribution chart (Fig. 3) and range of distribution of mature individuals (Fig. 9) coincided for each month. For this reason, it is assumed that maturity constitutes one of the factors for high-density distribution area for bigeye tuna being formed in tropical zone (WA, EB).

Relations between fishing rate and water temperature in the entire Indian Ocean

A total of 1,014 points at which observation of number of fishes caught and water temperature at hook depth of bigeye tuna in which KOUIKI-DOUJISEI (English ??) was secured to a maximum extent are as shown in Fig. 10, and number of hooks was 2,298,918 and number of fishes caught was 11,387.

Fig. 11 shows the relations between fishing rate per water temperature 1? , number of hooks and number of fishes caught in order to identify the optimum fishing temperature. As shown in the figure, hooks were set between water temperature 9-30? , and fishing water temperature for bigeye tuna was within the range of 10-30? . But number of fishes caught of bigeye tuna were small at 20? or over, and was 0 below 10? , and 85% of the total were fished in the water temperature zone of 10-20? . Out of it, with 12? as peak, the ranges where fishing rate were conspicuously high at 8.0 of o ver were in water temperature 11-13? . Further, fishing rate of bigeye tuna sharply declined at the lower temperature side in this 11-13? range, while gradually increased on the high temperature side. water temperature at fishing rate of 5.0 or over was at 10? or over at the low temperature side, and was 16? or lower (Fig. 11).

It is considered from these that the optimum fishing temperature is within the range of 10-16? .

Especially, according to the figure, fishing rate at 10? is high, but both number of hooks and number of fishes caught were smaller as compared with the 10? or higher. But numbers of hooks at 10? were relatively large values with 17,338, and number of fishes caught at 90, and fishing rate 0.52% --all showing relatively high values.

The average number of hooks used per fishing operation by Japanese tuna longline fishing vessels in the Indian Ocean in 1981 was 2,490 (National Research Institute on Far Seas Fisheries: report on the statistical research results by tuna longline fishing by fishing ground). On the basis of this figure, it corresponds to seven fishing operations. As fishing rate also showed a double level as compared with average rate of 0.26% for the Indian Ocean (National Research Institute on Far Seas Fisheries: the same report), the lower limit of the optimum fishing temperature was set at 10? in the present study.

Further, in Fig. 11, 16? , where fishing rate exceeds 5.0, were assumed as the upper limit of the optimum fishing temperature. Therefore, in the present study, water temperature 10-16? is determined as the optimum fishing temperature.

Relations between fishing rate and water temperature per area

In order to grasp the characteristics by the aforementioned area (WA, EB, MC, SD) with respect to the optimum fishing temperature of bigeye tuna, four areas were established as shown in Fig. 10.

Fig. 12 shows by area the relations between water temperature in the fishing strata for bigeye tuna and fishing rate. According to the figure, in the western tropical zone (WA) and eastern tropical zone (EB), fishing rate exceeded 5.0, and the range of its water temperature were 10-18? in western tropical zone (WA) and 10-15? in eastern tropical zone (EB). Fishing rate seldom exceeded 5.0 in the mid-latitudinal area (MC) and high latitudinal southern area (SD). The range of water temperature of fishing rate of 2.0 or over, which was relatively high. and it was found that it was 12-16? in the mid-latitudinal area (MC) and 10-17? in the high latitudinal southern area (SD).

In all the areas the cell with high fishing rate of bigeye tuna was in the neighborhood from the optimum fishing temperature at 10? -16? to around 1-2? . This shows that the optimum fishing temperature of bigeye tuna does not differ substantially according to areas.

Relations between fishing rate and dissolved oxygen amount

Fig. 13 show operation point to examine vertical distribution of fishing and areas established here. There areas of 20? N-15? S, 85? -90? E with relatively may data and materials were divided into 7 areas by 5-degree-square cell from Areas A to G. Distribution charts of number of hooks by depth of 40m and vertical distribution of fishing rate were made (given in Fig. 14a and Fig. 14b). In the same way as Fig. 11 used in obtaining the optimum fishing temperature, this stratum was made as the major distribution stratum, paying attention to fishing distribution stratum where fishing rate value exceeded 5.0.

According to Fig. 14a, in Areas A and B north of 10?N, longline hooks were set in the 40-240m stratum and the 40-280m stratum, respectively, but, the fishing rate of bigeye tuna in every stratum was 0 or close to 0.

With respect to vertical distribution of fishing in Area C, in the stratum of 80m or deeper, the stratum with fishing rate close to 5.0 was found in the 120- 200m stratum. In Area D, vertical distribution of fishing was found 120m stratum or deeper. Major distribution stratum with a fishing rate of 5.0 or over was found in the 160-240m stratum.

According to Fig. 14b, the fishing rate in Areas E-G at 0? -15? S south of the equator became higher in the 120m stratum or lower, and hook setting stratum was the deepest at 240- 280m.

Fig. 15 shows the dissolved oxygen amount of the two profiles in the vertical at 90? E in the area north of 30?S, and 104? E in the south of that border line. This figure shows that in the vicinity of 10? -20? N, the active stratum of dissolved oxygen amount was between 50- 100m, and the dissolved oxygen amount was 1ml/l or lower at the active stratum or deeper. isobath of dissolved oxy gen amount 1ml/l became deeper toward the southward direction in the area south of 10? N. After reaching around 200m at 5?N, extended to 600m.

The value of dissolved oxygen amount 1ml/l in Areas A and B (Fig. 15) was at around 100m, and the dissolved oxygen amount for larger depth was 1ml/l or lower.

As large bulk of hook depth were set at the depth of dissolved oxygen amount 1ml/l or lower in the Areas A and B, it can be assumed that fishing rate showed a figure close to 0 (Fig. 14a). In Fig. 15, fishing of bigeye tuna in the Area C-G located where the dissolved oxygen amount 1ml/l was deeper than Areas A and B and at 100-150m, it was 80 or 120m or deeper 80 or 120m (Fig. 14a , Fig. 14b).

Out of which, in the Areas E, F and G south of the equator (Fig. 14b), fishing rate was higher at the depth larger than 160m, and was the deepest stratum where hooks were set.

Japanese tuna longline fishing vessels catch bigeye tuna by setting hooks usually in the depth of 100-250m. As it was especially conspicuous in the Area A and B, it was considered that fishing was scarce because the dissolved oxygen at 100m or deeper where hooks were set was 1ml/l or lower.

Distribution of the optimum fishing temperature and dissolved oxygen amount versus fishing by area

Distribution of the optimum fishing temperature of bigeye tuna

The location of 1-degree-square cell where average water temperature was shown is given in Fig. 16. As stated in the previous chapter, the optimum fishing temperature of bigeye tuna in the Indian Ocean was 10-16? .

As water temperature generally declines along with water depth, it is estimated that the species are distributed from the depth of water temperature 16? to the depth of water temperature 10? .

In order to clarify the range of depth of the optimum fishing temperature in the entire Indian Ocean, Fig. 17a shows the depth of upper limit of 16 depth of the optimum fishing temperature, and Fig. 17b shows that of lower limit of 10? . The depth corresponding to the upper limit of 16? in the equator area was 150m, showing increase as north-south distance widens. For example, in the Arabian Sea corresponding water depth was 200- 250m, and in the east west area at 20?S it corresponded about 300m.

But at 30? S and 40?S, it moved to 100-150m and surface, respectively (Fig. 17a). According to Fig. 17b, the depth corresponding to the lower limit of 10? of the optimum fishing temperature was 400m in the equator area, and increased as in the case of an upper limit of 16? , the more longer distance it was separated in north-south direction.

For example, in the area west of 30?S, the maximum water depth was 700m but decreased to 100-200m at 40? S.

Upper limit of the optimum fishing temperature

The depth corresponding to 16? increases as north-south direction from the equator becomes larger in the Indian Ocean while, in the case of Pacific, east-west changes area conspicuous. In the equator area, for example, it was deeper in the western side and shallower in the eastern side.

Factors of difference in depth of water temperature 16? between the Indian Ocean and the Pacific are as follows: in the Pacific, upwelling arises in the water off eastern Peru, and the water of water temperature of water temperature 16 ? is lifted up to shallow strata by this upwelling. On the other hand, in the Indian Ocean, as there is no so conspicuous upwelling as in the Pacific in the eastern part, it is estimated that water temperature 16? is not lifted up to shallow strata. Fig. 18 shows vertical profile of water temperature with locations shown in Fig. 16.

Profile is shown in the north-south direction about the line of western 25? S-40? S-eastern 65? E in terms of average water temperature (?) by 1-degree-square cell of latitude-longitude.

As shown in Fig. 18, water depth of 16? gets gradually shallower as it moves southward from 300m at 24?N, touching the shallowest point of about 100m at 6? S, passing through 250m at 15? N. The largest depth of about 340m was reached around 22? S, and then turned upward emerging above the sea surface at around 38? S.

Centering on tropical zone, at 15? N-15?S, the water depth of the upper limit of 16? was about 100m around 6?S, and stayed around 150m on the whole, as at 10? N-10? S, except 150- 200m for 10°-15?N and 10°-15? S. Furthermore, at 15°-25?S belonging to southern mid-latitudinal area, the water depth at 16? was approximately around 250m or deeper.

Distribution of the minimum dissolved oxygen amount corresponding to fishing of bigeye tuna

Distribution of the minimum dissolved oxygen amount versus fishing of bigeye tuna

Fig. 19 shows, in dots, the locations obtained from depth distribution chart and materials that correspond to dissolve oxygen amount 1 ml/l.

The figure shows that the depth versus dissolved oxygen amount lml/l in the Indian Ocean was shallow in the east-west area north of 0? ~ 10? N which connect the Bay of Bengal and the tip of Somalia peninsula in the Arabian Sea to Sumatra. The shallowest points were 100~ 150m. The depth corresponding to dissolved oxygen amount 1 ml/l became abruptly deep to 500m south of the line connecting the tip of Somalia Peninsula to Sumatra Island.

Toward southern direction, the depth was 800m near the equator and 800m or deeper south of the equator. Fig. 19, which showed the distribution of density corresponding to dissolved oxygen amount ml/l, also showed that corresponding depth in the inner part of the Bay of Bengal and the Arabian Sea was is especially shallow at 100m or shallower.

CONCLUSION

With the aim to clarify bigeye tuna in the Indian Ocean, analysis was carried out on the following items:

- Spatio-temporal distribution of fishing area based on available materials accumulated in a long span of time
- Distribution of bigeye tuna fishing area by area
- The minimum dissolved oxygen amount as compared with the optimum fishing temperature and fishing
- Characteristics of distribution by area of the minimum dissolved oxygen amount versus the optimum fishing temperature and fishing.

The results of the research can be summarized as follows:

Spatio-temporal distribution of fishing area of bigeye tuna

Bigeye tuna has been fished in a wide area from 20? N-40?S in the Indian Ocean. Especially, the area in which bigeye tuna was believed to be distributed in high-density was high latitudinal southern area centering tropical zone and 30? S from the southern Arabian sea to the area off Java Island (Mohri *et al.*, 1991).

High-density fishing area of bigeye tuna was formed throughout the year in the tropical zone but reduced to the smallest size from April to September. By contrast, high-density fishing area expanded to the largest margin in high latitudinal southern area centering on 30? S from April to September. It can be estimated from this that bigeye tuna engage in seasonal movement in tropical zone and high latitudinal southern area (Mohri *et al*, 1997a).

Vertical distribution of fishing of bigeye tuna was within the range up to a water depth of about 60- 280m. Major distribution strata of fishing was 160- 280m in the tropical zone. But in the high latitudinal southern area centering on 30? S, there were no major distribution strata.

The lower limit depth of distribution range of fishing was 280m because of the absence of data and materials for 280m or deeper with respect to hook setting depth. Assuming from the fact that fishing rate increases along with the depth, it was conjectured that bigeye tuna of the Indian Ocean are distributed to the depth of 280m or deeper. (Mohri *et al.*, 1997b)

Distribution of mature bigeye tuna by fishing area

Fishes caught include mature individuals and non-mature individuals. The ratio of mature individuals was obtained per 5 square cell, on the assumption that this ratio is defined as the fishing rate of mature individuals.

The fishing rate of bigeye tuna maturity standard G.I.? 3.1 was generally high in low-latitudinal tropical zone, peaking about at 70%. It was low in the mid-latitudinal area at 0-30%, was almost 9% in the high latitudinal southern area. In the tropical zone where mature individuals were fished, the ratio of mature individuals underwent seasonal changes by area. In the western part, the ratio was high throughout the year, while in the eastern part, it was low in April September in the east-west area of 10? S and showed a higher trend in October - March.

This trend is considered due to the following reasons, as mentioned in the foregoing. mature individuals of bigeye tuna are distributed in large quantities in the area where there exist strata in which water temperature to 50m below the sea surface is 26? or higher (Mohri, 1999).

However, the condition that water temperature to 50m below the sea surface is 26? or higher is required for spawning and subsequent fostering of juveniles, and the stratum where mature individuals of bigeye tuna are usually found is the stratum of 10-16? with deeper water depth. In the season of southeastern monsoon, upwelling occurred in the area centering around off Somalia under influence of monsoon, and water temperature down to 50m from the surface falls below 26 ? . For this reason, the area where mature individuals are fishing is narrowed throughout the tropical zone. By contrast, it can be interpreted that, as there is no impact of upwelling in the season of northeastern monsoon, water temperature to 50m below the sea surface does not decline and the area where mature individuals are fished becomes wider.

Necessary conditions for fishing of bigeye tuna

A range of 10-16? was established based on the assumption that the range of water temperature where vertical distribution of fishing of bigeye tuna is large and fishing rate is 5.0 or over is the optimum fishing temperature of bigeye tuna in the Indian Ocean (Mohri et al. , 1996.) It was confirmed that the characteristics of the area where mature individuals are fished is that water temperature to 50m below the sea surface is 26? or over and that only non-mature individuals are fished in the area where the water temperature does not reach 26? (Mohri, 1998).

In the relation between vertical profile of dissolved oxygen amount and vertical distribution of fishing of bigeye tuna, the minimum dissolved oxygen amount versus the strata where bigeye tuna were fished was estimated as 1ml/l. This is due to the fact that fishing rate of bigeye tuna is 0 or close to 0 in the hooks set in the strata where dissolved oxygen amount stayed below 1ml/l.

Area-to-area distribution of necessary conditions for fishing of bigeye tuna

The depth corresponding to the upper limit of the optimum fishing temperature 16? is 150m in the area centering around the equator. In Arabian Sea, water depth 200- 250m, and in the eastern and western area of 20? S it showed approximately 300m. But it moved to 100- 150m at 30? S, and to the sea surface at 40? S.

The depth corresponding the lower limit of the optimum fishing temperature of 10? was 400m in the area centering on the equator, and in the area at 30? S, maximum value was 700m in the western part, and became shallower to 100-200m at 40? S. The area where water temperature to 50m below the sea surface in which mature individuals are fished gets 26? C or higher was found in tropical zone, while no such area were found in mid-latitudinal and high latitudinal southern area. The range of area where water temperature exceeds 26? shrank by the largest margin south of 10? S and east of 60? E in June-September when seasonal changes are conspicuous and southwestern monsoon reaches the strongest point. The range widened to the largest margin to the entire area south of 15? S in the period when northeastern monsoon strengthens centering on the winter in the Northern Hemisphere. This is due to the fact that the range with water temperature of 26? or over is narrowed in the period when southwestern monsoon strengthens as Somalia sea currents generates upwelling and lift up the low-temperature sea water of 26? or lower in the deep strata.

On the other hand, it is assumed that, in the season when northeastern monsoon is strengthened, the range of water temperature 26? never narrows as the upwelling does not occur. Given above is an interpretation of the aforementioned phenomenon. Characteristics of profile of the minimum dissolved oxygen amount 1ml/l versus fishing was that it was shallow in the east-west area around 0? -10? N which connect the Bay of Bengal and Somalia Peninsula and the Arabian Sea to northern Sumatra, with water depth staying at up to 150m. And the profile of dissolved oxygen amount 1ml/l got abruptly deep in the area south of the line connecting the tip of Somalia peninsula and Sumatra.

From the foregoing, the actual situation of spatio-temporal distribution of fishing area of bigeye tuna in the Indian Ocean. Further, it was elucidated that non-mature individuals, as its factors, move to tropical zone of with water temperature of up to 50m from the sea surface is 26? or higher, in the course of their way to maturity, and the optimum temperature affecting fishing of bigeye tuna is 10-16? , and required the minimum dissolved oxygen amount is about 1l/l.

We are confident that the results of the present study not only serve as promoting efficiency of fishing operation, as a guideline for selection of fishing ground, but will also provide basic data and materials for conservation and management measures for the resources, including control on fishing gear or fishing in the area where mature individuals are distributed.

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