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The environmental conditions of the tunas' maneuvering sphere in the Bay of Bengal*

Tsutomu MORINAGA**, Akihiro IMAZEKI**, Seiichi TAKEDA**
and Hisayuki ARAKAWA**

Abstract: In order to obtain information on the environmental conditions of the maneuvering sphere of tuna in the Bay of Bengal, the Indian Ocean, a series of investigations was conducted on board the T/S Shinyo-maru of the Tokyo University of Fisheries, in February 1987. Simultaneously with measurements of water temeprature, salinity, dissolved oxygen, underwater irradiance, and beam attenuation, experimental tuna-longline operations were also carried on in the same area. Regarding the water layer ranged from 38m to 69m, in which the group of tuna were caught, as their maneuvering sphere, its environmental data were obtaind through the observations, finding that those were 25.5 to 27.5 ℃ in temperature, 33.00 to 34.45 ‰ in salinity, 3.0 to 4.6 ml/l in dissolved oxygen content, 8.2 to 2.2 % in relative irradiance (i.e. total light), and 0.11 to 0.22 m^{-1} in beam attenuation coefficient, respectively. It was also understood that the maneuvering sphere of tuna was located just above the combined layer of thermocline, halocline, and oxycline or its upper part. Moreover, their sphere corresponded to slightly above or just within the high-turbidity water layer. From these results, it can be said that the tunas' living sphere of the Bay of Bengal is located in the shallowest water compared with any other tuna-fishing grounds all over the world. The reason of such a phenomenon may attribute to the location of the dissolved oxygen minimum layer locating in the subsurface layer of this oceanic water.

1. Introduction

The Bay of Bengal in the Indian Ocean is well-known as one of good fishing grounds of tuna group. The Bay has such an interesting characteristics that its surface-layer current shows, due to effects of seasonal changes of wind directions, a clockwise circulation pattern in spring while it shows a counterclockwise pattern in autumn and the salinity concentration of this layer is extraordinarily low due to enormous volume of water flown into the Bay from huge rivers. (WYRTKI, 1973)

The ecological studies on the tuna group made public in the past are mostly conducted from a viewpoint of their catch distribution in relation to their environmental conditions (UDA, 1960; KAWAI, 1969; SANDOVAL, 1971; HANAMOTO, 1975, 1986). For example, UDA (1960) informs that the range of inhabitant temperatures of tuna group is so wide as to be 11.0℃ to 32.0 ℃; HANAMOTO (1986) introduces data for inhabitant temperature, salinities, and dissolved oxygen among various ecological factors required for big-eye tuna of the Pacific Ocean indicating that the range of their inhabitant temperatures is so narrow as to be 10℃ to 15.0℃, the range of salinities of their inhabitant sphere is from 34.0‰ to 34.7‰ in the North Pacific Ocean and 34.5‰ to 35.5‰ in the South Pacific Ocean, and the minimum limit of their inhabitant dissolved oxygen is 1.0 ml/l.

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**Tokyo University of Fisheries, 5-7 Konan 4-chome, Minato-ku Tokyo, 108 Japan

So far the studies mentioned above, the discussions are developed along a very limited number of environmental factors such as water temperatures, salinities, etc.. Accordingly, it is afraid that the results of those studies might be fairly deviated from the real state of *in situ* environmental conditions.

In this study, therefore, such optical elements as underwater irradiances and turbidities, which were measured simultaneously with longlining operations in the Bay of Bengal, are added to such conventional items as temperatures, salinities, and dissolved oxygen, so that a step advanced approach to the real state of tunas' environmental conditions can be realized.

2. Method

The surveyed area is a central part of the Bay of Bengal in the Indian Ocean. Fig. 1 shows the distribution of observation stations. At stations numbered 1 to 7, catching experiments and environment measurements were simultaneously conducted, and at Stn. 8, only the latter were carried out.

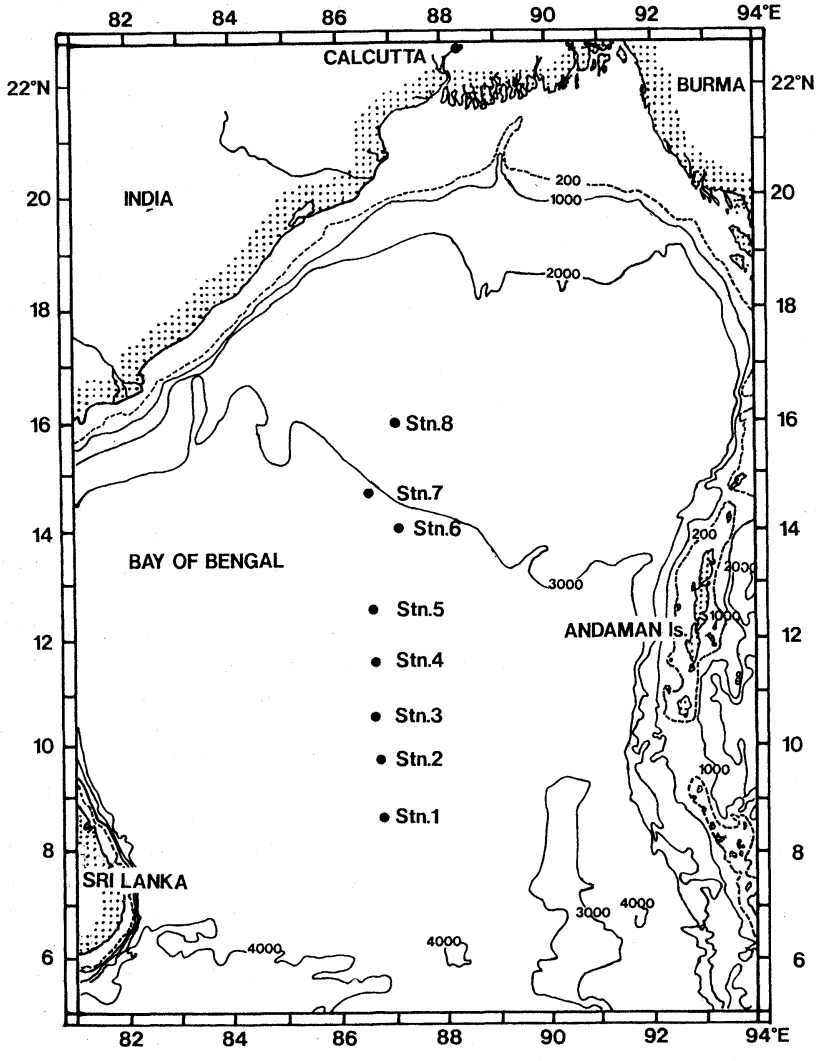

Fig. 1. Observation stations in the Bay of Bengal, Indian Ocean

The instruments for the measurement of the physical, chemical and optical environment included the CTD with DO sensor, underwater irradiance meter and *in situ* beam transmittance meter. The measuring accurancy of CTD (Mark IIIB, Neil Brown Co., LTD) was as follows; temperature, ± 0.005℃; conductivity, ± 0.005 mhos; depth, ± 0.1%. In addition, the values of dissolved oxygen were determined from the relationship between the observed and the analyzed values. (Fig. 2)

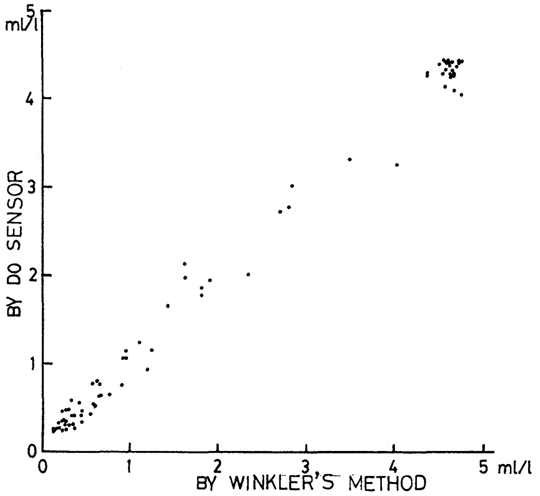

Fig. 2. Relationship between the observed and the analyzed values of dissolved oxygen.

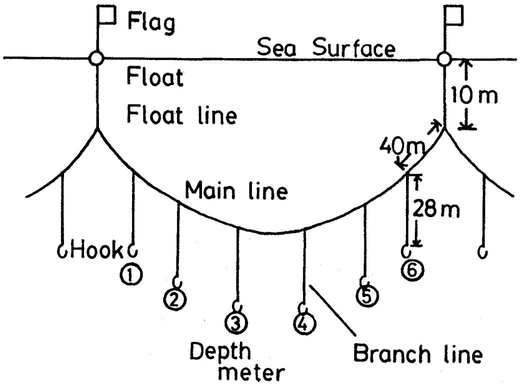

Fig. 3. Schematic representation of longline. The depth meter was hung on the third branch line.

The underwater irradiance meter (SR-8 type, Ishikawa Co., LTD) was equipped with eight interference filters with wavelengths of the maximum transmittance; 443, 481, 513, 553, 599, 663, 682 and 709 nm. A beam transmittance meter (XMS type, Martek Co., LTD) with a depth sensor was able to measure beam attenuation (centroid wavalength: 486nm) per meter.

In order to carry out observations of temperature, salinity and dissolved oxygen, a lowering of CTD was continuously made from the surface to a depth of 500 m or 1000 m. To measure irradiance, the meter was lowered at intervals of 10 m, from the surface to 50 m. Also, a beam transmittance meter was simultaneously lowered from the surface to a depth of 100 m. A beam attenuation coefficient was used as an indicator of the turbidity of water.

The tuna longline gear used in the catching experiment was the standard type with six branch lines per basket. As bait for tuna, frozen jack mackerel of which a fork length is 25 cm, was used hooking up a part of the dorsal fin. To evaluate precisely the depth of a branch line hook, the authors used self-recorded depth meter (BS-04 type, YANAGI Keiki Co., LTD). Each of the three depth meters was hung on the third branch line of the basket, which accounted for an interval of the one quarter of the total number of baskets in the line (Fig. 3). The depth (D) of each hook of a branch line was obtained by the Yoshiwara's expression (1951) as follows:

$$D = ha + hb + l \left[(1+\cot^2 \phi)^{1/2} - \{(1 - 2\, j/n)^2 + \cot^2 \phi\}^{1/2} \right]$$

where ha is length of branch line, hb is length of float line, l is half length of main line per basket, n is number of branch line added to l, j is order of branch line, and ϕ is cross angle between x-axis and tangential line at a supporting point of main line.

The number of baskets used in one operation was 150 at stns. 1 and 2, and 200 at the others. The lines were laid down from 4:00

to 7:30 a.m., and hauled up from 0:30 to 7:00 p.m..

3. Results and Discussion

3-1. Physical and Chemical Factors.

Fig. 4 is a temperature-salinity diagram based on the data collected from stn. 1 to stn. 8. According to the water mass classification of EMERY and MEINCH (1986), Bengal Bay Water (temperature, 25.0-29.0 ℃; salinity, 28.0-35.0‰) is above 500 m in depth, and below that, there is Red Sea Persian Gulf Intermediate Water (temperature, 5.0-14.0 ℃ ; salinity, 35.5-36.8‰). The salinity of the surface sea water of the former water mass changed by the Arabian Sea Water is said to be lower, ranging from 28.0 to 35.0‰.

Figs. 5a and 5b show the vertical distribution of temperature, salinity, and dissolved oxygen at stn. 1 and stn. 8, respectively. The temperature of the surface water at stn. 1 was 28 ℃, and decreased sharply with depth between 40 m and 200 m, indicating a form of thermocline. Below the thermocline, the water temperature decreased with depth from 14 ℃ down to 6 ℃ at a depth of 1000 m. On the other hand, the surface water temperature at stn. 8 was 26 ℃, which was 2 ℃ lower than that of stn. 1. Under the surface, the vertical distribution of temperature was similar to that of stn. 1.

In terms of the salinity, surface water at stn. 1 was 33.95‰ and increased suddenly at depths from 40 m to 120 m, showing a form of halocline. The depth of halocline coincided roughly with that of the thermocline. Below the halocline, the salinity was 35.0‰ and salinity inversion appeared at a depth of 120 m to 160 m. Below that, it again increased with depth, indicating a value of 35.0 ‰ at a depth of 400 m. Meanwhile, the value of the surface water at stn. 8 was 33.3‰ less than that of stn. 1. In the vicinity of 40 m deep, halocline was present on a small scale, and below that, it had a tendency to increase with depth the same as that of stn. 1. Yet, the phenomenon of

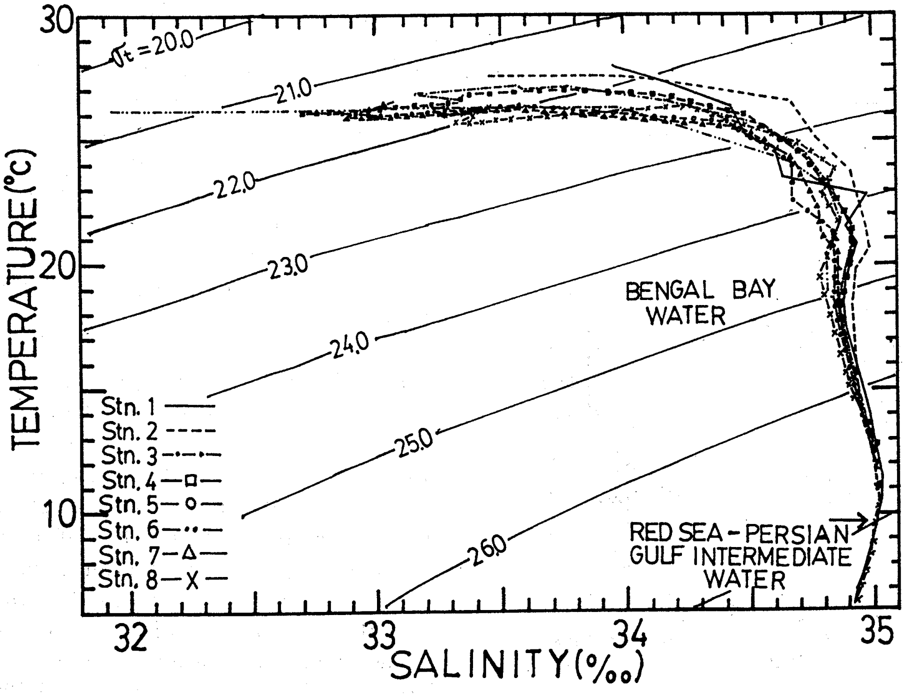

Fig. 4. Temperature-salinity diagram. Arrow in the figure means a boundary of each water mass.

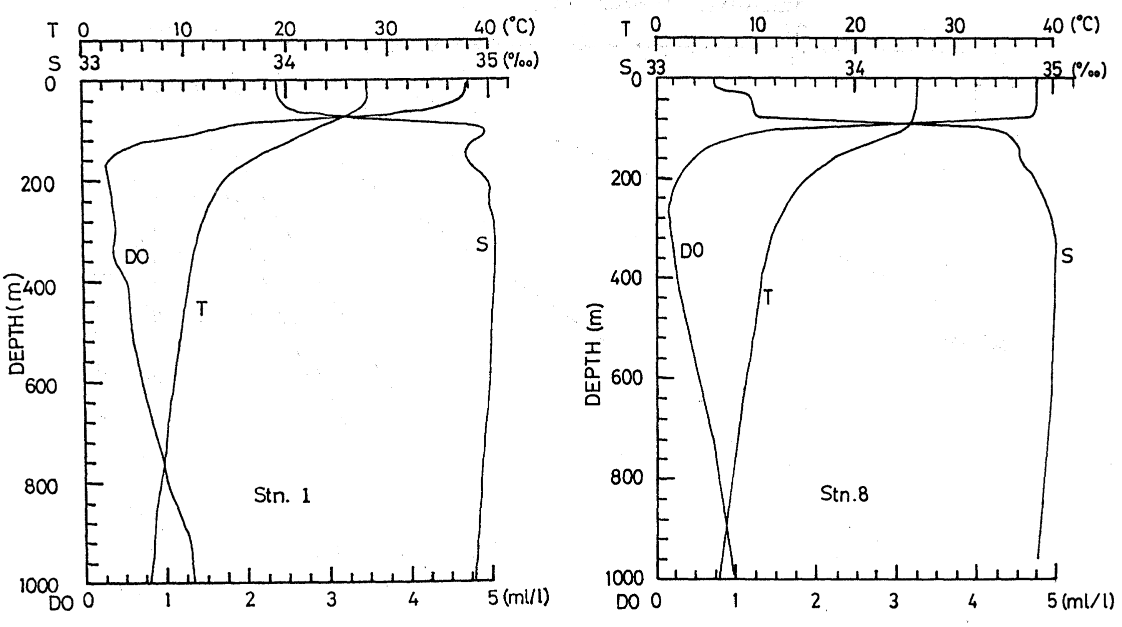

Fig. 5. Vertical distributions of temperature (T), salinity (S) and dissolved oxygen content (DO) at stn. 1and stn. 8.

inversion was present at a depth of 150 m.

The dissolved oxygen in the surface water at stn. 1 was about 4.6 ml/l, and at a depth from 40 m to 100 m, changed abruptly in the form of oxycline. At a depth of 120 m, the dissolved oxygen was 1.0 ml/l, and at a depth of 170 m, recorded the minimum value, 0.26 ml/l. Below that depth, the dissolved oxygen increased with depth, and registered 1.3 ml/l at a depth of 1000 m. Such the results of the dissolved oxygen that there are appearance of the minimum layer and an extremely wide range of dissolved oxygen concentration less than 1.0ml/l correspond to those brought forth by IIOE (International Indian Ocean Expedition). WYRTKI (1971) reports that this is one of features of dissolved oxygen distribution in the Bay of Bengal. Also, the type of depth distribution at stn. 8 was roughtly similar to that of stn. 1. However, one difference was found. It is that the minimum oxygen appeared at a depth of 260 m, which was 100 m deeper than that of stn. 1.

3-2. Optical Factors

Fig. 6 illustrates the depth profiles of downward spectral irradiance at stn. 4 as the representative of measurements. In the figure, the ratio of attenuation became larger according to the band of a short wavelength to a long one. Namely, the percentage of underwater irradiance at a depth of 30 m was 31.9 % for a blue light (481 nm), 22.3% for a green light (553 nm), and 4.03 % for a red light (599 nm), respectively. Also, the values of diffuse attenuation coefficients for downward irradiance were calculated. For instance, at a blue light it was 0.038 m^{-1}, which was about one third of 1.0m^{-1} (484 nm; HAGA and MATSUIKE, 1981) in the northern part of the North Pacific Ocean. According to the optical water mass of JERLOV (1976), this water belongs to the oceanic water type I", and is thought to be very clear.

In next, the depth distribution of water turbidity (beam attenuation coefficient; 486 nm) is shown in Fig. 7. Three stations (stns.

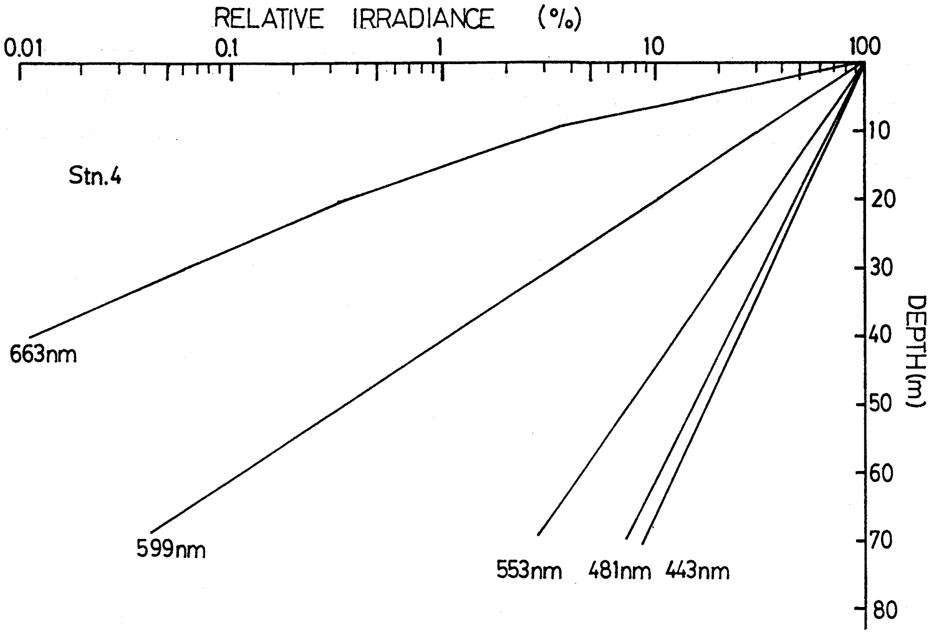

Fig. 6. Spectral distribution of underwater irradiance (relative value). Numeric on the figure is wavelength.

1, 4 and 7) were selected as the representative of measurements. The numerals in the figure increase in proportion to the degrees of turbidity of water. At stn. 1, the values of beam attenuation coefficient was nearly 0.12 m^{-1} at a depth of 0 m to 30 m, and between 40 m and 50 m, it reached the maximum value, 0.19 m^{-1}. Below that, it decreased with depth indicating a value of 0.07 m^{-1} at a depth of 100 m. At stn. 4, there was a little variance from the surface to a depth of 80 m, exhibiting ones of 0.13–0.16 m^{-1}. At stn. 7, the beam attenuation coefficient was 0.13–0.16 m^{-1} between the surface and a depth of 50 m, which was equivalent to those of stn. 1 above a depth of 40 m. At 70 m deep, it reached the maximum value, 0.18 m^{-1}, and below that, it decreased with depth, recording 0.10 m^{-1} at a depth of 90 m. As introduced above, the high-turbidity layer sometimes appears in the turbidity vertical distribution but sometimes does not according to circumstances. Furthermore it is understood that depth of water in which the high turbidity layer is configurated varies with localities.

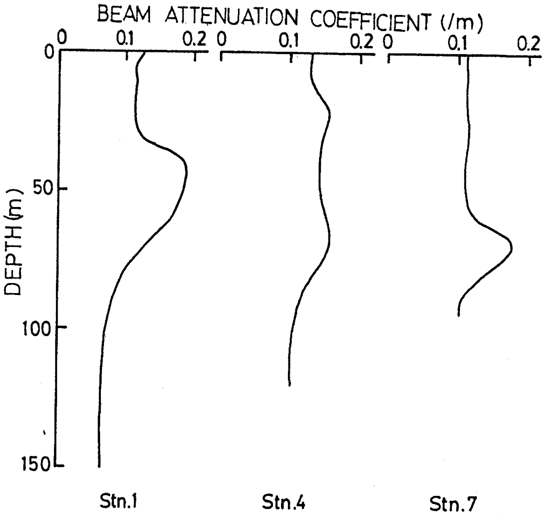

Fig. 7. Vertical distributions of water turbidity (beam attenuation coefficient) at stns. 1, 4 and 7.

3-3. *Environmental conditions of the tunas' maneuvering sphere*

Prior to discussing the characteristics of tunas' ecological conditions, it is reasonable to define their maneuveaing sphere.

In this sense, a figure of depths in which each tuna was caught by the longlining operations is provided as follows. Fig. 8 represents the catching depths of tuna and billfish by position. Symbols of solid circles, triangles and open circles indicate yellow fin, big-eye and narlin, respectively. From the figure, it can be understood that the range of catching depth is from 38.1 m to 69.0 m. In comparing the catching depth by species, marlin were caught in the shallowest water. Also, Table 1 shows characteristics of catching depth, and the thickness of the catching layer. It is found that the greatest thickness was 24.8 meters at stn. 7, and the least, 8.6 meters at stn. 4. Moreover, thickness of the catching layer changed with operation position, and averaged out to 16.5 meters.

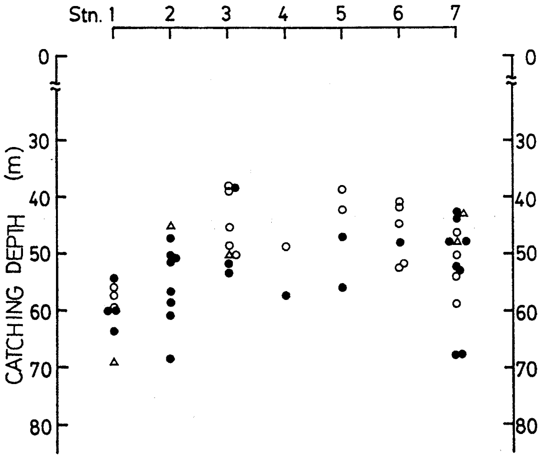

Fig. 8. Catching depth of tuna and billfish. Open circles, solid ones and triangles mean marlin, yellow fin and big-eye tuna, respectively.

Table 1. Characteristics of catching layer.

Position	Catching Layer(m)			
	Upper	Lower	Average	Thickness
Stn. 1	54.5	69.0	59.9	14.5
Stn. 2	45.2	68.5	54.5	23.3
Stn. 3	38.1	53.6	46.1	15.5
Stn. 4	48.9	57.5	53.2	8.6
Stn. 5	39.0	56.1	52.6	17.1
Stn. 6	40.9	52.5	46.6	11.6
Stn. 7	42.9	67.7	58.5	24.8

We, authors, assume that the sea layer in which tuna were caught in the Bay of Bengal is a fairly good approximation with the tunas' maneuvering sphere. Because, as explained in the preceding paragraph, the minimum oxygen layer appears in the surveyed sea regions and the layer of oxygen concentration lees than 1.0 ml/l, which is the minimum quantity required for supporting tuna's life (Hanamoto, 1986), is extended from 120 m to 800 m deep. Judging from these outcomes together with the findings of Wyrtki (1973), the said assumption can be reasonablly justified.

Figs. 9, 10 and 11 show the depth distributions of temperatures, salinuty and dissolved oxygen at each station, respectively. The dotted zones in the figures indicate the extent of the maneuvering sphere mentioned above. The temperature of the water within the maneuvering sphere ranged from 25.5 ℃ to 27.5 ℃ , and decreased toward the north.

Uda(1960) reported that the water temperature inhabitable for tuna ranged from 11 ℃ to 32 ℃. In the present paper, measurements were in the higher part of temperature range reported by Uda (1960). Moreover, the location of the maneuvering sphere was just above or the upper part of the thermocline. This finding differed from those of Suda *et al.* (1969) and Hanamoto (1975). They found that the catching depth of tuna was within the theromcline or below that level. Salinity within the maneuvering sphere ranged from 33.00‰ to 34.45 ‰, and decreased toward a northernly direction. These values are more smaller than 34.0-34.7‰ for big-eye tuna in the North Pacific Ocean, which Hanamoto (1986) obtained from inhabitable water temperature, using T-S curves. Dissolved oxygen in the water of maneuvering sphere varied from 3.0 to 4.6 ml/l. Our values are about three to four times as much as that of HANAMOTO (1986). According to HANAMOTO (1986),

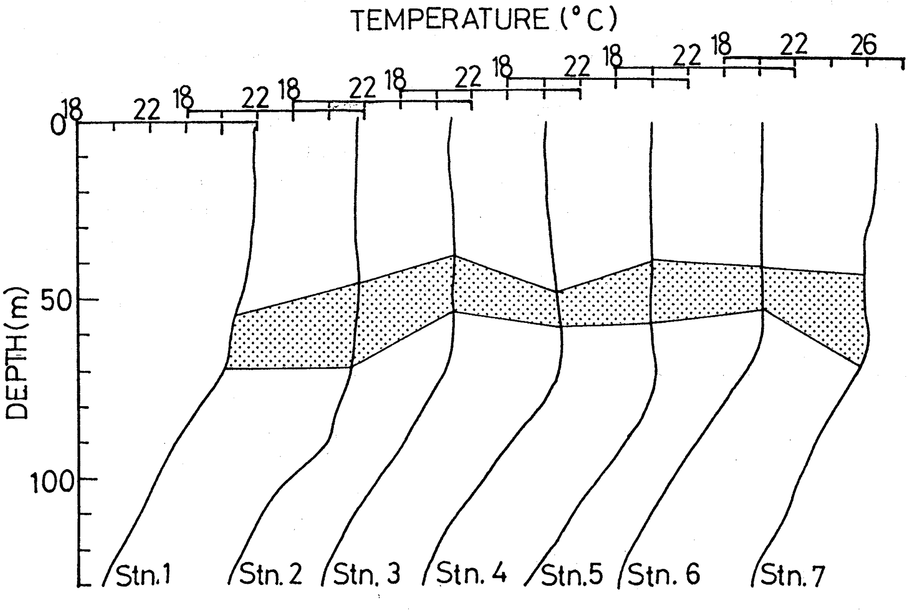

Fig. 9. Vertical distributions of temperature from 0 m to 130 m in depth. Shadow zone denotes the tunas' maneuvering sphere.

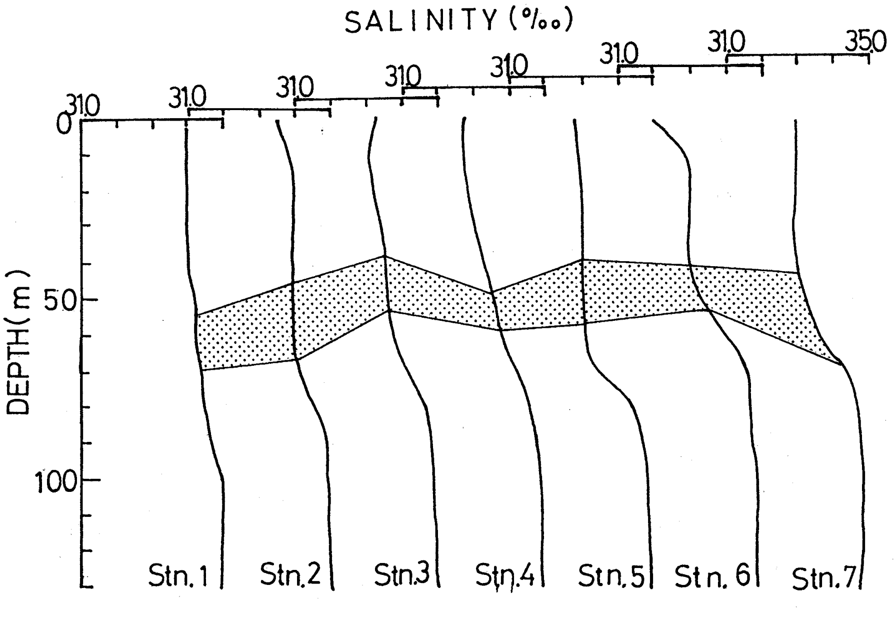

Fig. 10. Vertical distributions of salinity from 0 m to 130 m in depth. Shadow zone is shown as in Fig. 9.

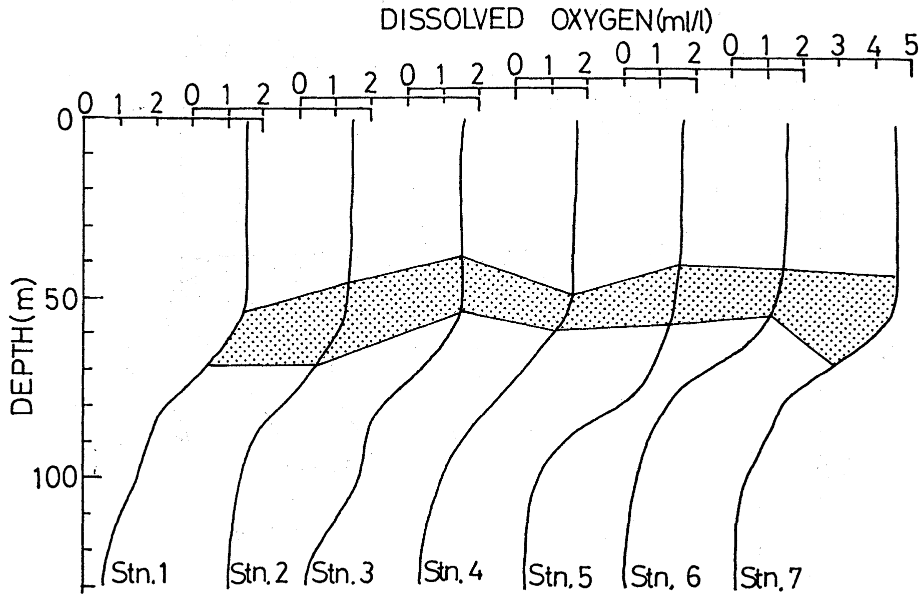

Fig. 11. Vertical distributions of dissolved oxygen content from 0 m 130 m in depth. Shadow zone is shown as in Figs. 9 and 10.

in situ measurements of dissolved oxygen inhabitable for tuna have never been conducted before. Therefore, these values are considered to be very important. Also, the maneuvering sphere was positioned just above or at the upper part of oxycline, as was observed at the thermocline and halocline.

With respect to a state of optical environment, Table 2 shows the relative values of downward irradiance by wavelength, and those of total light at the maneuvering sphere. In the table, it can be seen that the energy of the blue light was the greatest of them. On the other hand, the percentage of total light was 8.2 % at a depth of 38 m, and 2.2 % at a depth of 69 m. The ratio of attenuation on total light were almost equivalent to those of green light.

Fig. 12 illustrates the depth profiles of turbidity (beam attenuation coefficient) at each station. The dotted zone in the figure indicates the extent of the maneuvering sphere. Beam attenuation coefficients within that sphere ranged from 0.11 to $0.22m^{-1}$ (486nm). The highest recorded was double that of the Kuroshio area (MATSUIKE and MORINAGA, 1977). In addition, the location of the maneuvering sphere was just above or within the high turbidity layer. This might be related to migratory path for tunas' food-searching.

Table 2. Relative irradiance at the maneuvering sphere.

	Maneuvering	Sphere
Wavelength	Upper	Lower
(nm)	(38m)	(69m)
481	24 %	7.6 %
553	14	2.9
599	1.3	0.042
300-2500	8.2	2.2

Finally, let us discuss the maneuvering sphere of tuna in relation to the distribution of dissolved oxygen. YAMANAKA (1966) reported that the catching depth of tuna changed according to the location of a fishing ground. For instance, big-eye tuna in the Indian Ocean (except the Bay of Bengal) was

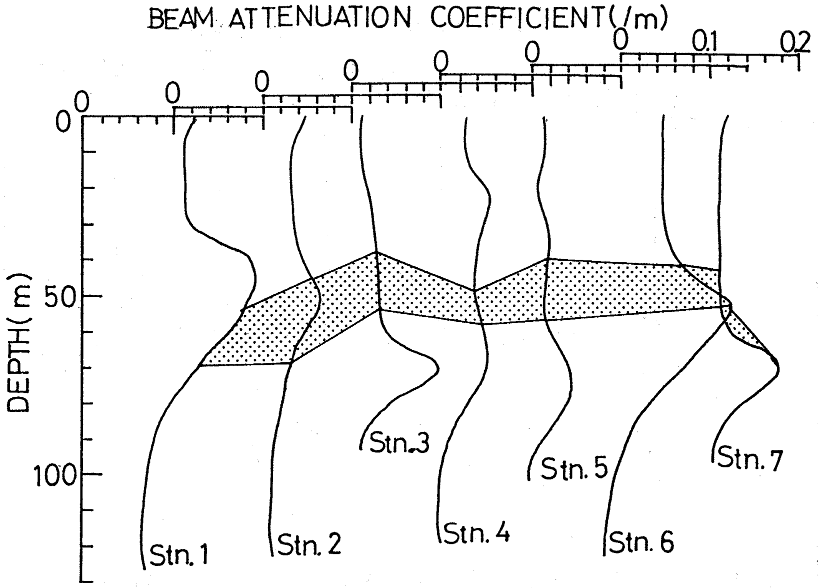

Fig. 12. Vertical distributions of water turbidity. Shadow zone is shown as in Figs. 9, 10 and 11.

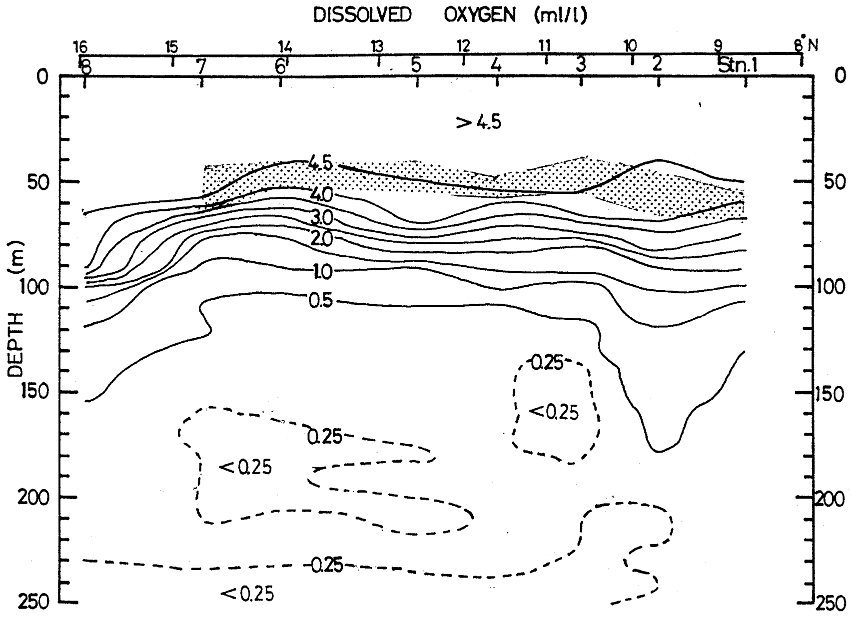

Fig. 13. Vertical profile of dissolved oxygen from 0 m to 250 m in depth. Shadow zone is shown as in Figs. 9, 10, 11 and 12.

catched at a depth of 300 m (YAMANAKA, 1966), and as for southern bluefin tuna, at a depth of 350 m (SHIBATA and NISHIMURA, 1969). Also, in the Solomon Islands in the

Pacific, the layer of yellowfin was at a depth of 40 m to 120 m (YAMANAKA and KUROHIJI, 1966), and albacore was at a depth of 90 m to 150 m in the Ogasawara Islands (YAMANAKA, 1966). Compared with the depths mentioned above, it is clear that the maneuvering sphere in the Bay of Bengal generally situated in shallower waters.

The dissolved oxygen in the water is considred to be a very important factor for survival of pelagic fish. For big-eye tuna, the dissolved oxygen minimum content must be 1.0 ml/l for survival (HANAMOTO, 1986), and for skipjack tuna, 3.5 ml/l along a migratory path (INGHAM *et al.*, 1977), and for yellowtail, 3.0 ml/l for swimming in an enclosure (YANAGI, 1986), respectively. Fig. 13 shows the vertical profile of dissolved oxygen content from the surface to a depth of 250 m in the Bay of Bengal. The dotted zone in the figure indicates the maneuvering sphere. As seen in the figure, it is understood that the minimum oxygen (content; <0.25 ml/l) appears at a depth of 150 m to 250 m. Moreover, a value of 1.0 ml/l (HANAMOTO, 1986) is observed at a depth of 100 m, and that of 3.0 ml/l (YANAGI, 1986), at depths from 60 m to 80 m. Accordingly, the vertical situation of the maneuvering sphere is said to be influenced by distribtion of dissolved oxygen content. In particular, the reason why the lower part of the layer was shallow is that the dissolved oxygen minimum layer appeared in the subsurface layer of the ocean.

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ベンガル湾におけるまぐろ•かじき類の環境条件

森永　勤・今関昭博・武田誠一・荒川久幸

要旨：インド洋・ベンガル湾のまぐろ・かじき類の環境条件を把握する目的で，1987年2月東京水産大学研究練習船神鷹丸において，従来の環境要素（水温・塩分・溶存酸素）に光学要素（水中照度・濁度）を加えた観測を延縄釣獲試験と同時に実施した。

釣獲水深（38mから69mまでの範囲）を生息領域とみなして環境条件を求めると，各値は次の通りであった；水温，25.0〜27.5℃；塩分，33.00〜34.45‰；溶存酸素量，3.0〜4.6ml／l；相対照度（全光），8.2〜2.2%；濁度（光束消散係数），0.11〜0.22m^{-1}（486nm）。又，生息領域の鉛直的位置は水温・塩分・溶存酸素の場合では各躍層の直上あるいは上端部に，濁度の場合では高濁度層の直上あるいは内部にそれぞれあった。これらの結果に基づくと，ベンガル湾における生息領域では下端部の水深が世界の漁場に比較して最も浅く，酸素極小層の亜表層への出現に影響されていると考えられる。