La mer 31: 11–18, 1993
Sociéte franco-japonaise d'océanographie, Tokyo

Underwater visibilities in different optical type water mass of the oceans*

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Abstract: In order to find how much the range of fish's vision is affected by the oceanic environmental conditions such as optical properties and turbidities of sea water, the relationships between the underwater optical environments and the tuna's visual perception limits for the different branch line leaders or the small fish as bait were investigated by means of taking the case of tuna longlining gear.

The intensities of underwater spectral irradiance in every tuna fishing ground of the world extremely vary with sea regions and depths of water. According to the Jerlov's optical classification of oceanic water mass, each water type of the Coral Sea in the Pacific Ocean, the western region of the Mediterranean Sea and the Andaman Sea in the Indian Ocean corresponds to Type IA to IB, IB, and II to III, respectively. When the steelwire-strand leader, of which specifications are 1.7mm in multifilament diameter, #28 and 3×3 plys, and the nylon-gut leader are 2.0mm in monofilament, #150 are set into water of those sea regions, the ranges of tuna's vision are 4.3, 3.6 and 2.7m for the former, and 1.2, 1.1 and 0.9m for the latter in each of the above-mentioned sea regions, respectively; and, in case of a piece of mackerel having its fork-length of 250mm, the ranges become 41, 28 and 16m, respectively.

1. Introduction

MORINAGA *et al.*(1990) introduce a study on the analysis of a phenomenon that the catch rate is fairly improved by applying a certain material to the fishing gear during their experimental tuna longlining operations in the Indian Ocean. In the first place, as the starting point of tuna's food-searching behaviours and their reactions to the fishing gear, the greatest distance at which tuna can be see each of the fishing gear or the small fish as bait is investigated through the survey conducted simultaneously with those fishing operations. As a results, it is known that the distance at which tuna can see the leader of branch line varies with the materials applied to it; that such the distance for the leader made of nylon-gut is shorter than that for the leader made of steelwire-strand, suggesting that the improvement in catch rate mentioned above attributes to this reason.

The traditional studies along the field of fishing technologies are concentrated on the fish's behaviours including their ecological investigations, but any efforts to solve the problems what are caused a certain action of fish are not developed at all. For example, it is not seldom that the only one kind or type of fishing gear is used in every sea region without paying an attention to different underwater environmental conditions from region to region, wasting efficiencies in catch rate and operating cost. One of major objects of this study is, however, to find how much underwater visibilities are varied with the oceanic environmental conditions such as optical properties and turbidities of sea water. Based on this concept, the distributions of underwater irradiance in different sea regions were obtained through the observations in the wide range of oceanic waters. Furthermore, the relationships between the underwater optical environments and the ranges of tuna's visual

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* Received December 8, 1992

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Table 1. The list of observation stations.

Ocean	Region	Observation Position	
Pacific Ocean	Kuroshio	33°54.5′ N	139°34.0′ E
	Off-Hawaii region	19°59.9′ N	139°53.7′ W
	Coral Sea	25°00.7′ S	163°00.0′ E
Indian Ocean	Andaman Sea	6°05.3′ N	96°40.8′ E
Atlantic Ocean	Central region	23°43.0′ N	33°09.0′ W
Mediterranean Sea	Western region	38°15.2′ N	7°48.2′ E

Table 2. The specifications and inherent contrasts of objective things.

Branch line	Material	Diameter	Inherent contrast
Wire leader	# 28, 3×3 plys	1.7 mm	6.3
Nylon leader	# 150, Monofilament	2.0 mm	1.1
Horse mackerel*	Dorsal fin**	250 mm***	16.0

* Bait ** Hooking method *** Fork length

perception for the different leaders or the small fish as bait were investigated by means of taking the case of tuna longlining gear.

2. In situ observations and optical properties of objects

The observations of underwater irradiance, which was regarded as one of representative factors to denote the underwater environmental conditions evaluated from an optical point of view, were carried on twice–one was in the winter of 1990–91 and the other was also in the winter of 1991–92–by the Umitaka-maru, Research and Training Boat of Tokyo Universities of Fisheries. As the observation stations shown in Table 1, the positions of these stations are distributed over a wide range of different oceanic regions covering the Pacific, Indian, Atlantic Ocean, and the Mediterranean Sea. Among the regions mentioned above, those in the Pacific, Atlantic Ocean, and the Mediterranean Sea coincide with the sea regions of tuna longlining operations reported by TAYAMA(1980).

A spectral radiant irradiance meter, type SR-8, manufactured by Ishikawa Sangyo Co., Ltd. was used for the observations of underwater irradiance and each spectral irradiance of such 8 wave lengths as 443, 481, 513, 554, 599, 664, 683, and 709nm was measured. The practical surveys were carried on at every depth of 0, 5, 10, 15, 20, 25 and 30m around the sun's meridian passage time.

A branch line including a leader with hook and a small fish as bait were chosen as the objective things in the observations. In respect to the optical properties of those things, the numerical values obtained by MORINAGA *et al.*(1990) through their water-tank experiments were also applied to this study (refer to Table 2).

3. Results and discussion

3–1. Distributions of underwater irradiance

Fig. 1 shows the distributions of relative values of irradiance. Among all the sea regions investigated, such two regions as the Coral Sea in the Pacific Ocean and the Andaman Sea in the Indian Ocean are chosen as the examples of the excellent underwater environments of which water has an outstanding optical transmittance. A common optical feature to both regions is that the wave length of the best light transmittance is 481 nm of blue light and the worst one is 709nm of red light. Furthermore, it is also common to those two regions that a certain wavelength range of spectral lights tends to decrease their transmittance from shorter wave lengths towards the longer ones according to such order as 554, 599, 664, and 683 nm. These optical characteristics are also seen at every observation station.

A water layer in which light transmittance decreases to 10% of its value in the water surface locates in the depth of 90m for the spectral light of 481 nm, 33 m for 554 nm, and 4m for 709 nm in the Coral Sea. And each corresponding value in the Andaman Sea is 25 m, 20.5 m and 3.2 m, respectively. This means that the transmittance of each spectral light considerably varies with

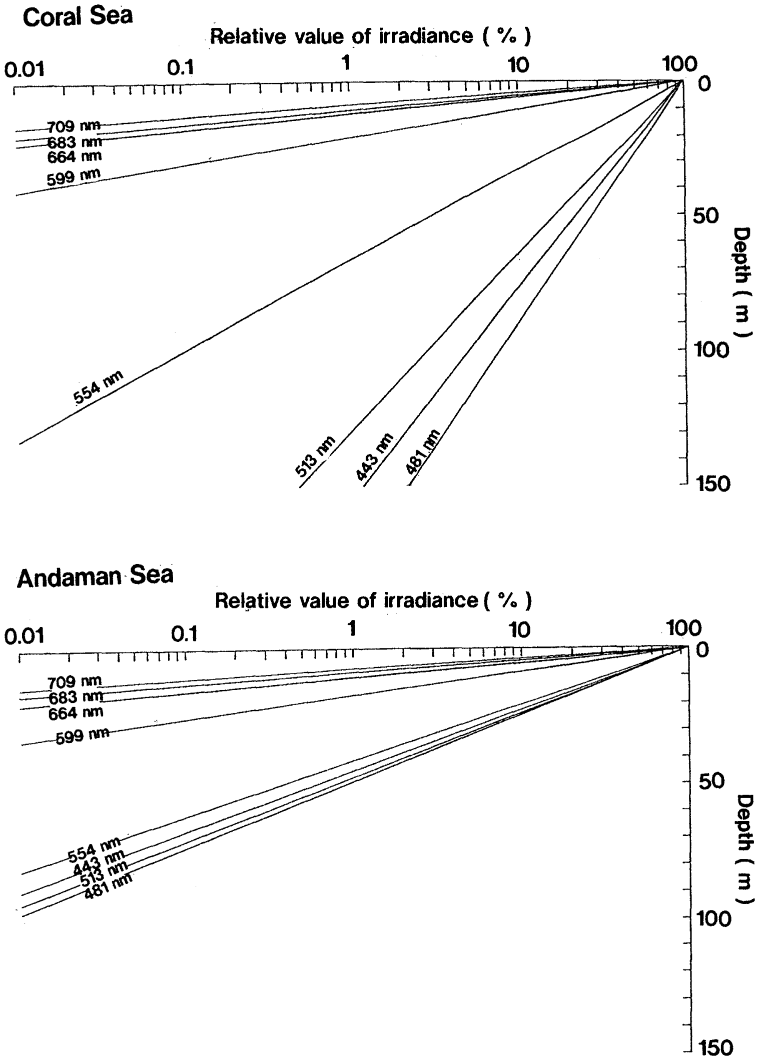

Fig. 1. Depth distribution of spectral relative irradiance in the Coral Sea and the Andaman Sea.

the sea regions as well as the wave lengths.

Fig. 2 exhibits the distribution of spectral light energies classified by depth in the same sea regions as those in Fig. 1. In comparison of both diagrams, there are little differences in light attenuation rates on the longer wavelength side than around 550 nm, while those on the shorter wavelength side are very large. The cause for such phenomena attributes to the attenuation due to light absorption of sea water itself so far as the longer wavelength side is concerned, while that in case of the shorter wavelength side is due to light absorption as well as scattering by suspended matters and dissolved substances in sea water. This suggests that there are much differences in quantities of suspended matters and dissolved substances in different sea regions.

An optical classification of oceanic water mass is brought forth by JERLOV (1951, 1976) as a result of his global-scale observations of underwater spectral irradiance in the different oceans in the world. According to his study, there are 5 types of oceanic water mass in the world which are designated as I, IA, IB, II and III in order of the better light transmittance. For instance, the values of attenuation coefficient for irradiance, of which wave length is 475 nm, in each watermass type are expressed as 0.018

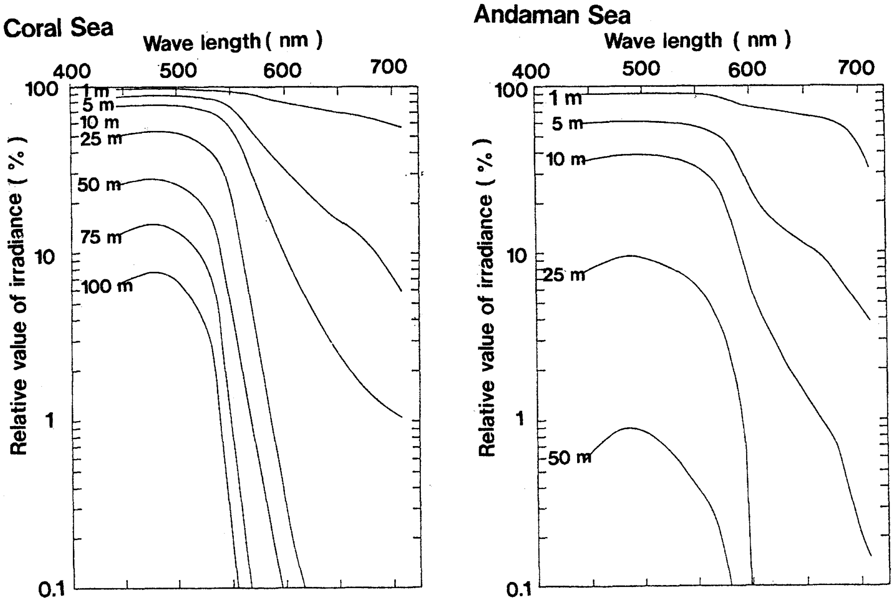

Fig. 2. Distributions of spectral light energies by depth in two sea regions.

Table 3. The values of attenuation coefficient for downward irradiance in each sea region.

Location	Wave Length (nm)							
	443	481	513	554	599	664	683	709
Kuroshio	3.50	3.29	4.62	7.34	22.9	39.9	45.8	57.5
Off-Hawaii region	2.88	2.81	3.93	7.03	22.8	40.1	45.4	61.0
Coral sea	2.74	2.55	3.57	6.93	22.4	39.5	45.4	56.6
Andaman Sea	10.3	9.42	9.76	11.2	27.6	45.8	53.6	65.0
Atlantic Ocean	2.88	2.74	4.08	6.83	22.8	39.5	45.4	57.1
Mediterranean Sea	4.59	4.39	5.53	7.92	23.7	41.0	46.8	59.0

$(\times 10^{-2} \mathrm{m}^{-1})$

m^{-1} for water type I, 0.025 m^{-1} for IA, 0.033 m^{-1} for IB, 0.062 m^{-1} for II and 0.116 m^{-1} for III, respectively. All the measurements obtained through the above-mentioned observations for this study are closely examined on the basis of the optical classification by JERLOV (1976) (refer to Table 3). Thus, it is concluded that each type of oceanic water mass in the Kuroshio region, the off-Hawaii region, and the Coral Sea region of the Pacific Ocean, the Andaman Sea region of the Indian Ocean, the central region of the Atlantic Ocean, the western region of the Mediterranean Sea almost coincides with the Jerlov's Type IB, IA, IA to IB, II to III, IA and IB, resepectively.

3-2. Ranges of fish's visual perception for objects

Whether a fish can visually percept an object submerging in the sea or not is decided by such three factors as the size of the object, its contrast to the background, and brightness in the water (NAKAMURA, 1989).

An apparent size of any submerged objects visually percepted is decided by a visual angle (i.e. an observation direction angle) at an observation position. The apparent size of the object is related to the visual angle by the following equation,

$$D=2 \cdot \mathrm{r} \cdot \tan(\phi/2) \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots (1)$$

where D stands for dimensions of the object, r denotes a distance from the observation position to the object, and ϕ indicates the visual angle or the observation direction angle of the object.

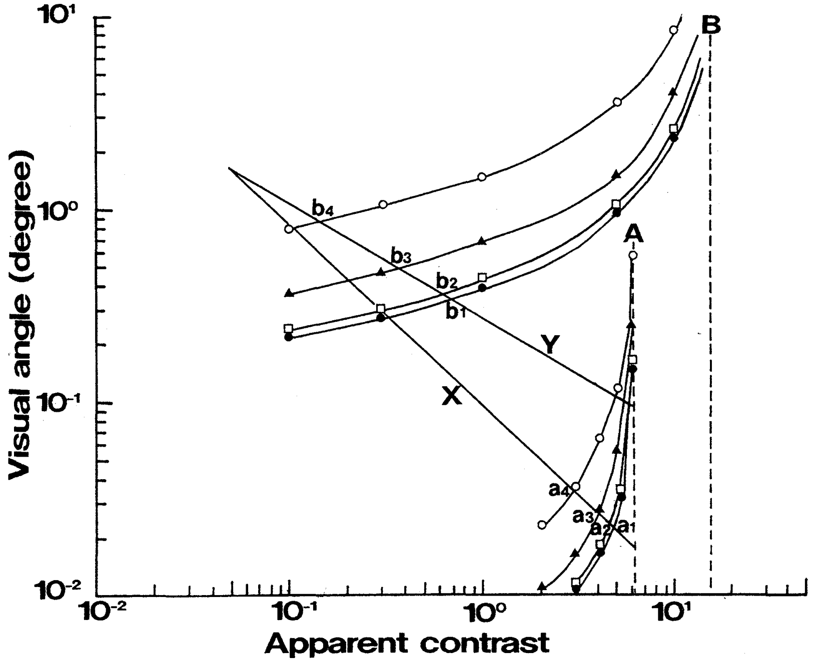

Fig. 3. Relation between apparent contrast and visual angle with regard to a wire leader and a small fish.

Symbols ●, □, ▲ and ○ denote the Coral Sea, the off-Hawaii sea region, the Mediterranean Sea and the Andaman Sea, respectively. Broken lines A and B show inherent contrast of 6.3 for the steelwire-strand leader and 16.0 for the small fish as bait, respectively. The lines X and Y exhibit the relationships between visual angle at the limit of discrimination and apparent contrast. Points a and b stand for the positions crossed with the lines X and Y, respectively.

It is introduced by DUNTLEY (1963) that the inherent contrast of the submerged object is related to its apparent contrast by the following equation,

$$C(r)=C(o)\exp(-\alpha\cdot r)\cdot Bb(o)/Bb(r) \quad \cdots\cdots\cdots\cdots(2)$$

where $C(r)$ stands for an apparent contrast at a distance r from the object, $C(o)$ denotes an inherent contrast at a position of the object, α is a beam attenuation coefficient, and $Bb(o)$ and $Bb(r)$ are values of radiance from backgrounds at the position of the object and at a distance r from the object, respectively.

Furthermore, with regard to underwater brightness, it is considered on the assumption that the environment is favoured with the sufficiently bright conditions.

Based on the above descriptions, Fig. 3 is arranged to show the relation between the apparent contrast and the visual angle (i.e. observation direction angle) resulted by the use of equations (1) and (2). The two object things discussed in the diagram are the steelwire-strand leader and the small fish as bait. Besides, the diagram is arranged on the basis of such assumptions that the $Bb(o)/Bb(r)$ of the equation (2) is evaluated as 1, and the value (α) of beam attenuation coefficient is estimated to be 3 times as much as the attenuation coefficient for downward irradiance (TYLER, 1968). The values of beam attenuation coefficient of which wave length is 481 nm, in each sea region are calculated to be 0.078 m^{-1} in the Coral Sea, 0.084 m^{-1} in the off-Hawaii sea region, 0.13 m^{-1} in the Mediterranean Sea, and 0.28 m^{-1} in the Andaman Sea, respectively.

According to Fig. 3, if the visual angles to see the steelwire-strand leader become smaller (i.e. if the distances from the observing position to wire leader become longer), the values of apparent contrasts would become gradually smaller than those along the broken line A, showing the successive contrast reductions. In case of the

Table 4. The ranges of tuna's vision for the branch line leaders and small fish as bait in each sea region.

Oceanic region	Beam attenuation coefficient	Visibilities		
		Wire (D:1.7mm)	Nylon (D:2.0mm)	Mackerel (L:250mm, H:70mm)
Coral Sea	$0.078\ m^{-1}$	4.3 m	1.2 m	41 m
Off-Hawaii region	0.084	4.2	1.2	39
Mediterranean Sea	0.13	3.6	1.1	28
Andaman Sea	0.28	2.7	1.96	16

Letters D, L and H denote diameter, fork length and body height, respectively.

small fish as bait, the apparent contrasts also show a similar reducing tendency. But, since the size or thickness of the branch line itself is very small, such a tendency is affected by the background near the object and scattering lights due to suspended particles existing in the light path as introduced by MORINAGA *et al.*(1985). The visible range is controlled by the two elements of visual angle and apparent contrast. According to the NAKAMURA's method (1989), a limited visible range in the clear water is obtained by means of regarding the line visual acuity as 0.90 which is 5 times as much as the visual acuity of skipjack tuna (SCHWASSMANN, 1974) and the contrast threshold as 0.05 (HESTER, 1968) and shown by the straight line X in the diagram. Thus, the line X exhibits the relationship between visual angle at the limit of discrimination and apparent contrast, its right-upper side is the visible part and its left-down side is the invisible part. The respective intersection, a_1, a_2, a_3 and a_4 of the line X and the curved line of the fishing gear expresses the visual angle and apparent contrast for the visible limit in each sea region.

On the other hand, in case of the small fish as bait, the limit of visible range is obtained by means of regarding the visual acuity of skipjack tuna to be 0.18 (NAKAMURA, 1968) and the contrast threshold to be 0.05 and exhibited by the line Y. The respective intersection, b_1, b_2, b_3 and b_4 of the line Y and the curved line of the bait in each sea region is shown in the diagram for the same purpose as the case of the fishing gear.

3-3. Underwater visibilities in different optical type water mass

Table 4 shows the limits of underwater distances at which a fish can see the branch line and the bait in each sea region. Those visible distances in the Coral Sea which has the clearest water as proven through the underwater irradiance observations are greatest, comparing with other sea regions, indicating 4.3m for the wire leader, 1.2m for the nylon leader, and 41m for a piece of mackerel as bait. But, these visible distances in turbid water of the Andaman Sea which locates not a long way off the coastal water become considerably shorter showing almost 65% to 80% for the leader and approximately 40% for a mackerel as bait, of those values in the Coral Sea. Such the visible distances in the Bay of Bengal of the Indian Ocean are introduced by MORINAGA *et al.* (1990) for the fishing gear and the small fish as bait of which specifications are identical with those of this study, informing that the values in the Bay of Bengal are identical with those in the Mediterranean Sea. According to the above descriptions, it is understood that the visible distances from a fish to a certain object considerably vary with the underwater optical environments.

So far as the underwater optical environment is concerned, it comes to be known through Fig. 2 that the blue light is most prominent in the spectral light composition at the layer from 50 m to 100 m deep. This is considered to be related to the discovery, which is introduced by KOBAYAHSI (1962) and KAWAMURA *et al.* (1981), that the greatest sepctral sensing value of tuna's eye is found in the spectra of which wave lengths are more or less 490 nm.

As for a galvanized steelwire filament and a monofilament of nylon-gut as materials of the leader, NAKAMURA *et al.* (1991) reported recently that both have the values of spectral reflection radiance in the wavelength range from 380 to 760 nm, but they are nothing to do with the wave length, and the reflection rate of the former is larger as much as almost 5 times of that of the latter. It is also revealed by them that the greater part of hues (i.e. almost 90%) for a colored steelwire-strand leader provided with a rust-preventive coating is a red color. This phenomenon coincides with the fact proven by MORINAGA *et al.* (1992) that, so far as visibilities of any objects in clear sea water, the red colored object is harder to see than the blue or green colored ones. Such an aspect of affairs can be satisfactorily proven also from a viewpoint of improvement in catch rate of tuna. As for the hues of the bait fish in opposition to the case of fishing gear, the blue-tone colors of small bait-fish's skin are theoretically more useful because of their longer range of sight. It can be said, therefore, that each skin color of mackerel and saury which are used nowadays for tuna longlining operations through a varied experience meets well with such a requirement.

Acknowledgements

The authors express their sincere thanks to Dr. K. MATSUIKE, professor of Tokyo Univ. of Fisheries for his valuable comments on this paper. Also, thanks are due to Prof. Y. SAOTOME, Captain of the T/S Umitaka-maru of Tokyo Univ. of Fish., and the crews for their support during the observations.

This study was partially supported by a grant from the academic foundation of 100th anniversary of Tokyo Univ. of Fish..

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大洋の光学的水塊分類における水中視認距離

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要旨：水中視認距離が海洋環境（海水の光学的性質や濁り等）でどのように変化するかを知る目的で，まぐろ延縄操業を例にとり，海中光環境と漁具（釣り糸）あるいは餌（小魚）における視認限界との関係を調べた。

世界のまぐろ漁場における海中分光照度の分布は海域や水深で顕著に変る。JERLOV の光学的水塊分類に従うと，太平洋・珊瑚海域では水型ＩＡ～ＩＢ，地中海・西部水域ではＩＢおよびインド洋・アンダマン海域ではⅡ～Ⅲにそれぞれ該当する。これらの海域の水中に，太さ（直径）1.7mmの釣元ワイヤ（＃28, 3×3）や2.0mmのナイロンテグス（＃150，モノフィラメント製）の各釣り糸を設置した場合，まぐろの水中視認限界距離はそれぞれの海域では前者4.3，3.6および2.7m，後者1.2，1.1および0.96mである．また，尾又長250mmの鯖の餌ではそれぞれ41，28および16mである。