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Distributions of underwater spectral irradiance and optical environments of tuna fishing grounds in the three oceans*

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Abstract: During the two winter seasons from 1990 to 1992, the survey of the underwater irradiance was carried on by the R/T Umitaka-maru of Tokyo University of Fisheries, covering the global-scale wide range waters.

By the aid of high-efficiency spectral irradiance meter, the authors measured the irradiance values from the surface to 30m deep for 8 spectral lights of which respective wave length was 443, 481, 513, 554, 599, 664, 683, and 709 nm. Simultaneously with those optical surveys, experimental tuna longlining operations were conducted in the same regional waters.

The underwater spectral light of which wave length is 481nm has the best light transmittance, and that of 709nm has the worst one. So far as the spectral lights of which wave lengths between 443nm and 683nm are concerned, they decrease the values in light transmittance according to the order of wave lengths from the short to the long one. The shorter wave length of 481nm has wider differences in light transmittance than those of the longer one of 709nm. The water mass of the Coral Sea in the Pacific Ocean is the very clean water which comes under the water type IA according to Jerlov's optical classification. In those regions the turbidity does not change with a secular variation. It is common to every fishing ground between 50m and 150m deep and locating from Lat. 20° to 40° N. that the blue light among all the spectral ones is most predominant; that the absolute and relative values of irradiances are in constant ranges of 50 to 320 μw/cm^2, and 0.2 to 1.2%, respectively. This suggests a possibility to use these optical data as a clue for locating the tuna fishing ground.

I. Introduction

Oceanographic observations of underwater spectral irradiance were carried out approximately 40 years ago by JERLOV, Swedish optical-oceanographer, covering a globally wide areas (1951). He measured light transmittances in water by the use of a simple underwater irradiance-meter attached with broad band filters, and, based on the light transmittance distributions for 16 wavelength spectral lights within the spectrum range from 310nm to 700nm, established a classification of such 5 water types as I, IA, IB, II, and III which are arranged in the order of better light transmittances. (1964, 1968) The well-known map that he captioned "Regional Distribution of Optical Water Types" were referred to the various scientific fields. (JERLOV, 1976) MATSUIKE (1973) intended to grasp the solar energy distribution throughout all the space from the sky to the depths of the sea, employing the same type of instrument as that of Jerlov, and measured the underwater spectral irradiance so far in the Kuroshio of the Pacific Ocean, the Indian Ocean, and the Antarctic Ocean. He determined quantitatively seasonal solar energies in the different oceans based on regionally different optical properties of the sea waters in each oceans, and connected those with rough estimates of productivities in the ocean. Thereafter, with the rapid advance of electronic equipments and the substantial progress in

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technologies, a number of high-performance submersible spectroradiometers were developed one after another by many scientists such as TYLER and SMITH (1966), BAUER and IVANOFF (1970), SUGIHARA and INOUE (1976) and OKAMI *et al.*(1981); and the accumulation of data in respect to all the spectral lights was made possible.

Water temperatures, salinities, dissolved oxygen and so far as the environmental elements required for tuna distributions or establishments of tuna fishing grounds have been investigated since quite a long time. (UDA, 1960; KAWAI, 1969; INGHAM, 1977; HANAMOTO, 1985; KURITA *et al.*, 1991) In addition to these elements, optical and audio properties in the water, osmotic pressures, intensitie of magnetic fields can be also considered as the other elements. CAREY *et al.* (1981) report that the movement of the species of boardbill swordfish, *Xiphias galdius* is traced by the use of a bio-telemetry system, finding that this species live in the very deep waters during the daytime and move up in the shallow waters during the nighttime. Thus, it comes to be understood that optical elements in the water are closely related to their distributions and movements as described above. On the other hand, SAKAMOTO (1985) informs that the living sphere of boardbill swordfish is obtained from the locus of their movements mentioned above, and the underwater irradiance values distributed there are trially calculated, finding that the irradiance value in their living depth during the daytime seems to be equal to that during the nighttime. But, there still remains many problems related to the distributions of spectral irradiance and those variations in the different oceanic waters for future studies.

Through the optical observations extended for a two-year period in the three oceans of the world such as the Pacific, the Indian, and the Atlantic Ocean and their adjacent seas, the authors collected the measurements for this study, keeping the identification of instrument, in respect to the irradiance values for 8 different wavelength spectral lights in the waters from the surface to 30m deep. Simultaneously with those optical observations, experimental tuna longlining operations were carried out also in the same regional waters. Based on the collected measurements, such the subjects as (1) the distributions of underwater relative irradiances and spectral light energies in different regional waters, (2) the optical classification of different water masses, and (3) the optical environment of the tuna living sphere are investigated as described hereinafter.

2. Method and Instruments

A series of optical observation was carried out twice–one was in the winter from 13th December 1990 to 3rd March, 1991 (This period will be abbreviated to "in the first period" hereinafter.) and other was also in the winter from 3rd December, 1991 to lst March, 1992 ("in the second period" hereinafter) – during each long-distance cruise of the Umitaka-maru, Research and Training Boat of Tokyo University of Fisheries. Fig. 1 shows the locations of observation stations distributed in different oceans. As seen in Fig. 1 the observation statios count 9 in the first period and 18 in the second period, counting up 27 stations in total. All the stations in the first period lie from east to west in the Pacific, the Atlantic Ocean, and Mediterranean Sea of the northern hemisphere and those in the second period extend from north to south in the Pacific Ocean, the Bay of Bengal in the Indian Ocean, and South China Sea of the both hemispheres. Accordingly, it can be said that distribution of the observation stations covers the global wide-range oceanic waters.

Experimental tuna-longlining operation during the first period were carried on in the offshore water of the Hawaiian Is. in the North Pacific Ocean, and those during the second period were operated in the Bay of Bengal in the Indian Ocean. The positions of those experimental operations are also shown in Fig. 1.

Measurements of underwater irradiance were carried on by the use of the spectral irradiance meter, type SR-8, manifuctured Ishikawa Sangyo Co., Ltd. This meter was incorporated with 8 pieces of built-in interference filters, each of which enables to pass the specific wavelength light among those of 443, 481, 513, 554, 599, 664, 683, and 709nm. Each of the bandpass (50% points) is about 10nm. Besides, the photodiode having an excellent photosensitivity was employed as many as 8 pieces for the light

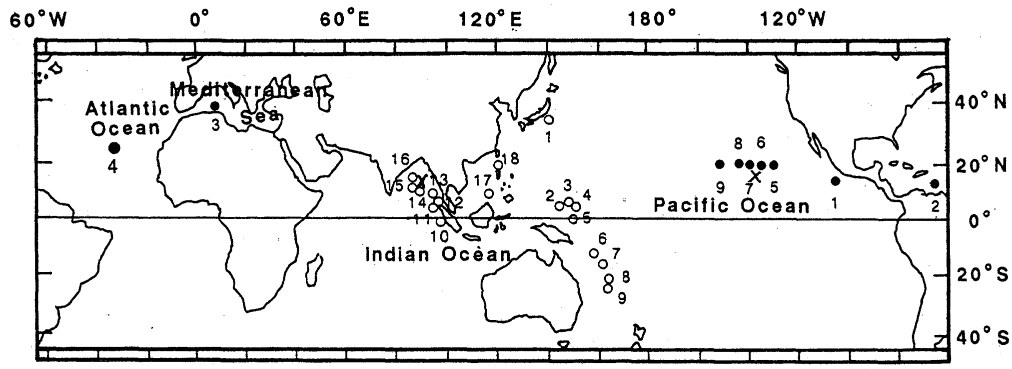

Fig. 1. Regional distribution of the observation stations.
Solid circles show the observation stations in the first period (from 1990 to 1991), and open ones in the second period (from 1991 to 1992). Symbol X indicates the position of tuna long-lining operation in each period.

sensation elements of this meter. The calibration of the meter was corrected under the standard light source of DXW120V/100W every time before the ship's departure for the navigation. The observation of underwater irradiances was generally conducted around the time of sun's meridian passage when it came up to the maximum altitude. Each measurement was fundamentally carried out at 7 spots arranged at every depth of 5m in the water between the sea surface (practically from the surface to lm) and the depth of 30m. As a matter of fact, however, the distribution of underwater irradiance in the water more than the depth of 30m was also investigated, extending up to the euphotic zone where the value of irradiance was reduced to 1% of its surface value. (JERLOV, 1976)

The conventional tuna longline gear was employed for the experimental fishing operation, setting the gear early in the morning and hauling in the afternoon. The depth of water, in which tuna was caught, was calculated from the depth of the hook attached at the end of the leader(shelf-recorded depth meters were hung on the leader).

3. Results and Discussion

3-1 Distributions of relative irradiance and spectral light energy in the oceans and their adjacent seas

Figs. 2(a) to 2(d) show each distribution of relative irradiance in the different regions such as the Coral Sea in the Pacific Ocean (Stn. 52-9), the central area in the Atlantic Ocean (Stn. 49-4), the western area in the Mediterranean Sea (Stn. 49-3) and the Andaman Sea in the Indian Ocean (stn. 52-12). Each solid line exhibited in those Figures stands for the wave length of the respective spectral light transmitted. It is a phenomenon in common to those sea regions that the wave length of 481nm has the best light transmittance and that of 709nm has the worst one. It is also common in those regions except the Andaman Sea that the wave lengths so far between 443nm and 683nm constantly keep the same order of descending light transmittance. Such a tendency is traced at 25 stations out of all the observation stations. In respect to the wave lengths of 481, 554, and 709nm, the depth in each ocean of which the irradiance value is reduced to 10% of its surface value is listed in Table 1. It is understood through this talbe that the shorter wave length of 481nm has wider differences in light transmittance than those of the longer wave length of 709nm in each ocean.

Fig. 3 exhibits the distributions of spectral light energies both in the Coral Sea of the Pacific Ocean where its water mass shows the best light transmittance and in the Andaman Sea of the Indian Ocean where its water mass constantly indicates the worst one throughout all the surveyed regions. In comparison of the relative irradiance values in both regional waters, the differential gaps are large on the shorter wavelength side of the border, 550nm, while those the longer wavelength side are very small. The cause of such phenomena can be concluded that the attenuation of the longer wavelength

Table 1. Depth in each ocean which the irradiance values is reduced to 10% of its surface value.

Region Light	Pacific Ocean (Stn. 52-9)	Atlantic Ocean (Stn. 49-4)	Mediterranean Sea (Stn. 49-3)	Indian Ocean (Stn. 52-12)
481 nm	90 m	88 m	52 m	25 m
554 nm	34	33	28	21
709 nm	4.0	3.7	3.5	3.2

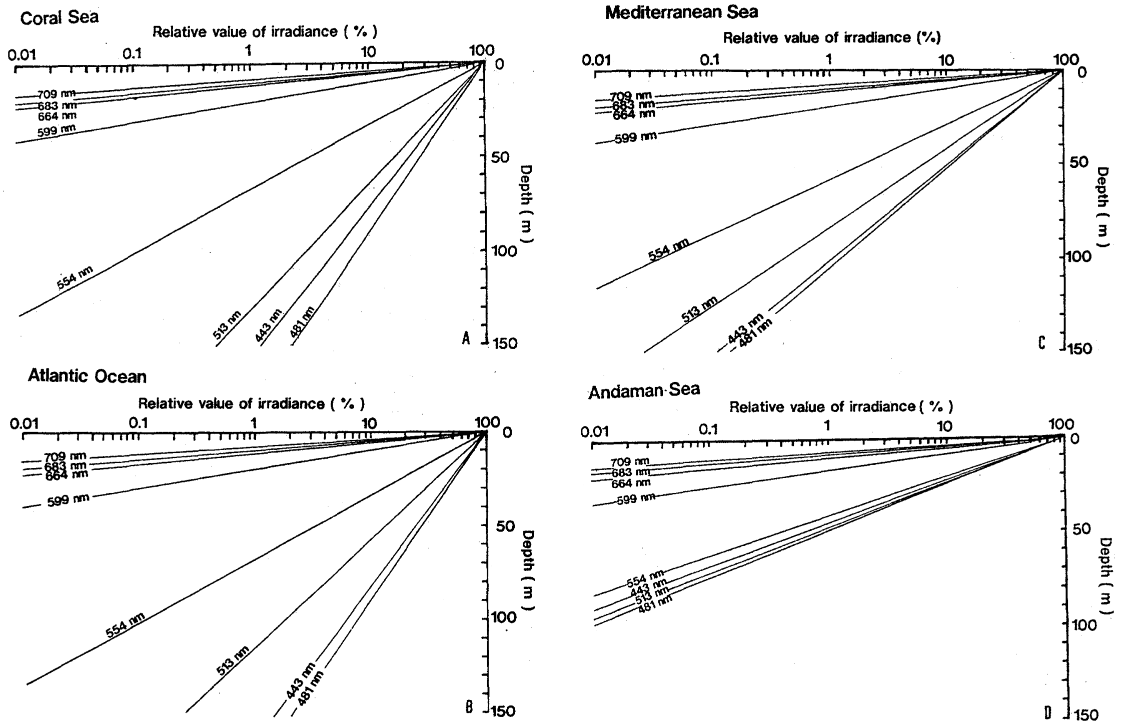

Fig. 2. Depth distribution of spectral relative irradiance in four sea regions.
(A) Pacific Ocean (Stn. 52-9) (B) Atlantic Ocean (Stn. 49-4)
(C) Mediterranean Sea (Stn. 49-3) (D) Indian Sea (Stn. 52-12)

lights mainly depends on the light absorption by sea water itself while that of the shorter wavelength lights is due to the light absorption and scattering by suspended matters and dissolved substances in sea water. This suggests that there is a wide difference in concentration of suspended matters and dissolved substances between both regional waters. Such a result of this study agrees with the achievements made by TYLER and SMITH (1970), MATSUIKE (1973), MOREL *et al.* (1974), and OKAMI *et al.* (1978).

3-2 Classification of optical water types in all the surveyed regions

An optical water type classification in all the observation stations is shown in Table 2. This classification is achieved according to the system of JERLOV (1951;1976). As listed in the Table, each water mass in the offshore region of the Hawaiian Is. and the Coral Sea region in the Pacific Ocean corresponds to the water type IA, respectively; each one in the Kuroshio, the Caribbean Sea, and the western region of the Mediterranean Sea comes under the water type IB; each water mass of Mexican offshore region in the Pacific Ocean, the Andaman Sea in the Indian Ocean and the South China Sea agrees with a water type between II and III. Since 4 to 5 observation stations are particularly assigned to

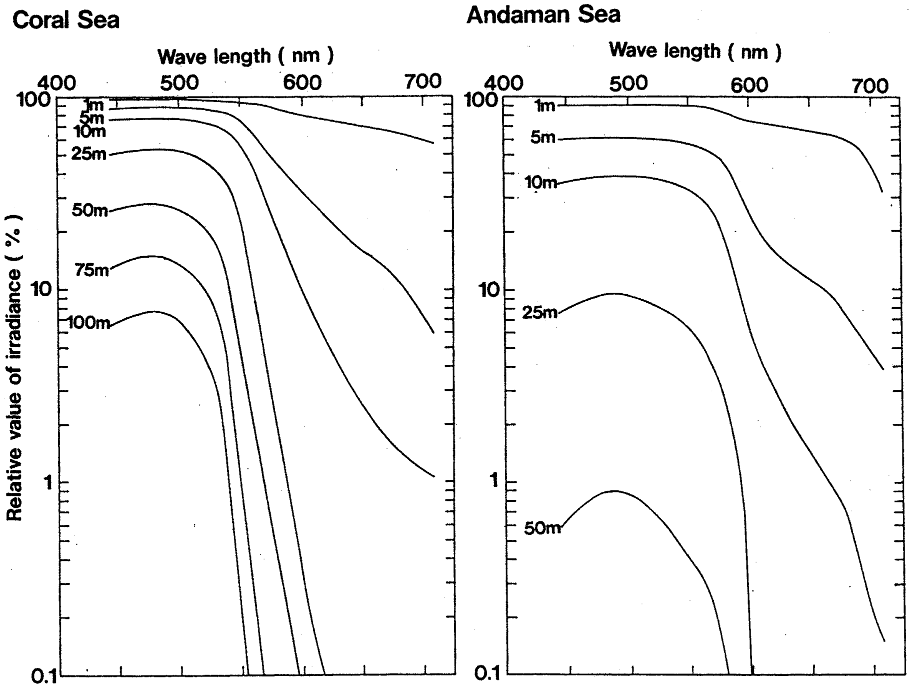

Fig. 3. Distributions of spectral light energies by depth in two sea regions.

Table 2. An optical water type classification in all the observation stations. Asterisk* stands for a dominant type.

Ocean	Sea region	Number of station	Optical water type
Pacific O.	Kuroshio reg.	1	IB
	Off Hawaii reg.	5	IA*-IB
	Off Mexico reg.	1	II-III
	Equatorial reg.	4	IB-II*
	Coral Sea reg.	4	IA*-IB
Atlantic O.	Caribbean Sea reg.	1	IB
	Central reg.	1	IA
Indian O.	Bay of Bengal reg.	3	IB*-II
	Andaman Sea reg.	2	II-III
	Off Sumatora Is. reg.	2	IB-II
Mediterranean Sea	Western sea reg.	1	IB
South China Sea	Northern and southern sea reg.	2	II-III

each of the offshore region of the Hawaiian Is., the equatorial region off New Guinea, and the Coral Sea in the Pacific Ocean, the water types in those regions are considered as a result of the mean optical measurements. Anyhow, it is interesting that those water types agree with the classification achieved by Jerlov almost 25 years ago. This means that the turbidity in those regions scarcely change with a secular variation. On the other hand, each water mass

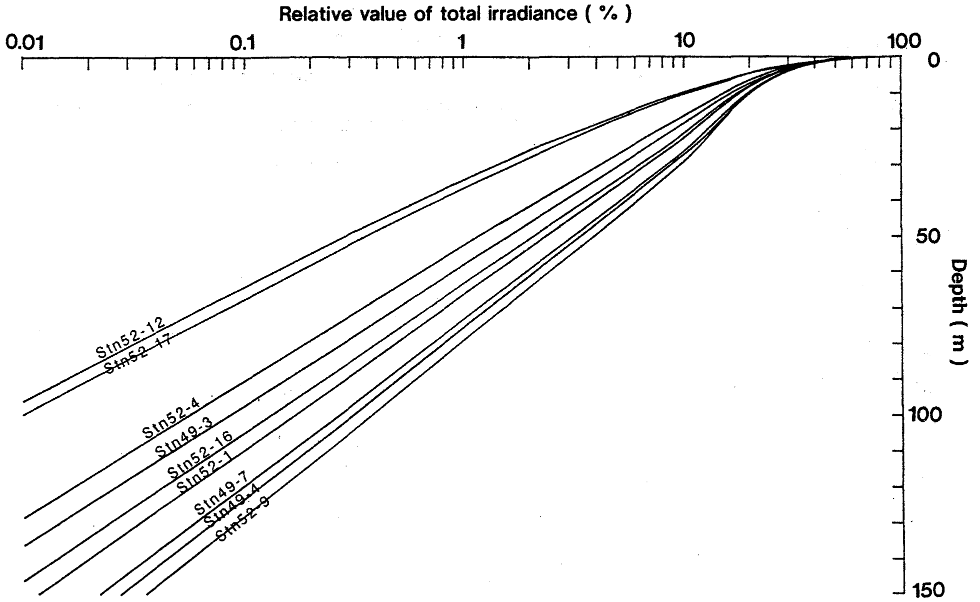

Fig. 4. Depth distribution of relative total irradiance in each sea region.

of the region located not far from the continents or the islands comes under one of other water types of which light transmittances are inferior to those in the regions mentioned above. It can be reasonably said that such a phenomenon is due to the effect of muddy water run out of the land into the sea.

Fig. 4 is prepared on the basis of Table 2, showing the distribution of underwater energies of all the spectral lights in the major regions. In those regions, the depth, in which underwater irradiace is reduced to 1% of its surface value, varies considerably with the different regions. For example, such the water exists in 79m deep in the Coral Sea (Stn. 52–9), 66m deep in the Kuroshio(Stn. 52–1), 59m deep in the Mediterranean Sea (Stn. 49–3) and 34m deep in the Andaman Sea (Stn. 52–12), respectively. Besides, the respective irradiace value (i. e. the percentage of the surface irradiance value) in 50m deep is 4.8%, 2.3%, 1.6% and 0.28% according to the order of the regions stated in the preceding paragraph.

3-3 Optical environment in the tuna fishing ground

The oceanic regions, in which experimental tuna longlining operations for this study were carried out, are the offshore water of the Hawaiian Is. in the Pacific Ocean and the Bay of Bengal in the Indian Ocean. And, most of the regions surveyed for this study agree with those of major tuna fishing grounds of the world (TAYAMA, 1980). Based on such an assumption that the fished depth of tuna is equal to the range of living sphere, the optical environments of tuna fishing grounds in the Pacific, the Indian, the Atlantic Ocean and the Mediterranean Sea are investigated. The fished depths of tuna are between 65m and 110m deep in the offshore water of the Hwaiian Is., which are resulted from experimental operations carried out in the first period, and between 60m and 120m deep in the Bay of Bengal conducted in the second period. Thus, these ranges in depth in the two regions resemble each other. Fished depths in other fishing grounds are obtained on referring to the relevant records and literatures or through the vertical configurations of physical properties in the different oceans. The results are between 150m and 380m deep in the Coral Sea in the Pacific Ocean (SAITO, 1992), between 50m and 150m deep in the central region of the Atlantic Ocean (KAWAI, 1969), and between 50m and 100m deep in the western region of the Mediterranean Sea (YAMADA, private information), respectively. Under the circumstances, it

Table 3. Absolute and relative values of underwater total light in the tuna maneuvering spheres of the every fishing ground. Tuna maneuvering spheres shown by asterisks* were obtained on referring to the literatures.

Item \ Fishing ground		Bay of Bengal	Off Hawaii reg.	Coral Sea	Atlantic O.	Mediterranean S.
Tuna maneuvering sphere (m)		60-120	65-110	150-380*[1]	50-150*[2]	50-100Z*[3]
Total light	Absolute value (μw/cm^2)	12-360	42-315	0.02-13	8-891	17.6-336
	Relative value (%)	4-120 $\times 10^{-2}$	2-15 $\times 10^{-1}$	6.9×10^{-7} ~ 3.6×10^{-2}	3-330 $\times 10^{-2}$	8.4-160 $\times 10^{-2}$

can be said that the fished depths of tuna in the objective fishing grounds for this study is in the range from 50m to 150m deep.

The values of underwater spectral light energy in the depth of 50m to 100m are little on the longer wavelength side while those are large on the shorter wavelength side as shown in Fig. 2. This means that the spectral blue light transmitted there is more predominant than any other spectral lights. This agrees with the fact discovered by KOBAYASHI (1962) and KAWAMURA *et al.*(1981) that the best luminous efficiency wavelength band of tuna's eye is more or less than 490nm which is the major wave length of the blue light. Such a phenomenon that the responsive wave length of tuna's light sensing organ agrees with the most predominant wave length in the water of maneuvering sphere gives us a great deal of interest.

In Table 3, the absolute and relative values of underwater total irradiances in the tuna maneuvering spheres of the every fishing ground are tabulated. In this case, the practical measurements of 2.1 to $3.6 \times 10^4 \mu$w/cm^2, of which mean value is $2.7 \times 10^4 \mu$w/cm^2, are used for the irradiance values in the surface water (i.e. practically from the surface 0 m to 1 m) and the percentages with which the underwater irradiance values reduced in accordance with the depths of water are quoted from Fig. 4. As seen in the Table, the underwater irradiance values of the tuna maneuvering sphere differ according to each fishing ground, and their differential ranges are very wide indicating 2×10^{-2} to $8.9 \times 10^2 \mu$w/cm^2. The cause of this wide differential gaps can be attributed to such a fact that tuna in the Coral Sea of the Pacific Ocean is able to move up to the very deep water in which underwater irradiance shows an extremely small value. This small irradiance value of 2×10^{-2} to $1.3 \times 10 \mu$w/cm^2 can stand in comparison with $3 \times 10^{-1} \mu$w/cm^2 which is reported to be the irradiance value in the surface water during the full moon night (WATERMAN, 1974). It might be considered, therefore, that, so far as the daytime around the sun's meridian passage is concerned, the tuna species inhabit in the dark environment (SAKAMOTO, 1985). Besides, it can be found out also from Table 3 that the irradiance in the tuna maneuvering sphere of every fishing ground except that of the Coral Sea is within a certain range of around 5×10 to $3.2 \times 10^2 \mu$w/cm^2.

The practical underwater irradiance value fluctuates according to its value in the sky which changes every season and every moment. Under the circumstances, the further discussion about the underwater irradiance in the tuna maneuvering sphere will be proceeded by the use of its relative value. As seen in Table 3, the relative irradiance value considerably varies according to the different fishing grounds as same as the case of its absolute value; the relative irradiance value except that of the Coral Sea is within the range of 0.2 to 1.2%. These values are very small comparing with those of 2.2 to 8.2% found in the Bay of Bengal (MORINAGA *et al.*, 1992). The reason can be considered that because the minimum concentration layer of dissolved oxygen located in the Bay of Bengal comes up to the subsurface layer, the tuna living sphere moves up to the extremely shallow water of which depth is from 38m to 69m. Accordingly, the underwater irradiance in the tuna maneuvering sphere is common to every fishing ground which is located from Lat. 20° to 40° N., keeping a constant brightness equivalent to approximately 1% of the surface irradiance value. This suggests a possibility to use the knowledge of the regional irradiance distribution in the ocean for locating the tuna fishing ground.

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三大洋における海中分光照度分布とまぐろ漁場の光環境

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要旨：1990年から1992年までの間の二回の冬期に、東京水産大学研究練習船海鷹丸で地球規模の広範囲な海域において、著者等は高性能な水中放射照度計を用い、各海域の表層から水深30mまで八波長（波長；443, 481, 513, 554, 599, 664, 683, 709nm）の分光照度を測定した。同時に、まぐろ延縄による釣獲試験をも実施した。

海中光の透過が最も良い波長及び悪い波長はそれぞれ481nmと709nmである。透過の悪くなる波長の序列はほとんどの海域で、短い波長443nmから長い波長683nmへの移行である。光透過の深度の海域別相違は短波長側で大きく、長波長側で小さい。太平洋珊瑚海の水塊は JERLOV (1976) の光学的水塊分類の oceanic type IA に該当し、非常に清澄な海水である。この海域の濁りの永年変化は少ないものと考えられる。太平洋、インド洋、大西洋及び地中海における北緯20度から40度付近のまぐろ漁場に共通して、生息領域（水深50～150m）の分光分布では青色光が卓越している。又、そこにおける海中照度（全光）の絶対値及び相対値は、それぞれ 50～320 μw/cm^2 及び 0.2～1.2%と一定範囲にある。このことはまぐろ漁場探査の一つの手掛りを示唆している。