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Colors of submerged objects observed from a viewpoint above the sea surface*

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Abstract: In order to understand the quantities of marine resources and control the properties of sea waters by means of the optical measurements above the sea surface,such subjects that chromatic differences of sea waters in different sea regions and the reasons why those differences are brought forth, chromatic shiftings of colors of the submerged objects observed from a viewpoint above the surface; and depth limitations of discriminating colors of the submerged objects from colors of sea waters were analyzed through the *in situ* oceanographical surveys and indoor experiments as well.

(1) The CIE colorimetric system defines color of water, in terms of chromatic nomenclature, to be "dark Purplish Blue" of which dominant wavelength is 474nm in the Bay of Bengal, "dark Blue" of 480nm in the Bay of Sagami, "dusky Olive Green" of 554nm in the entrance district of Tokyo Bay, and "dark Olive" of 580nm in the interior part of Tokyo Bay. Colors of sea waters are different in localities, of which the largest cause is a difference in quantities of organic suspended substances among different sea regions.

(2) Original color of a colored board seen in the air shifts to different color due to turbidities caused by suspended matters and dissolved substances. For examples, all of blue color of which dominant wavelength is 480nm, green color of 514nm and red color of 597nm seen in the air shift to hues, each of 477, 483 and 478nm when they are submerged into clear water locating in 20m deep in the Bay of Bengal of which degree of turbidities is more or less 0.11m^{-1}. Those hues are, in turn, going to be converged into an identical color of sea water itself of which dominant wavelength is 474nm, as the depth of water increases.

(3) Depth limitations of descriminating, with naked eye, each aerial color of the colored boards mentioned above from colors of sea waters themselves are 13.4m for blue, 12.0m for green, and 9.1m for red in clear water of the Bay of Bengal, and 0.9m, 0.8m, and 1.0m for each color in muddy water of the interior part of Tokyo Bay, of which degree of turbidities is more than 4.6m^{-1}.

(4) Depths of water, within which any submerged objects could be visually recognized from a viewpoint above the surface, substantially vary with colors of the submerged objects and degrees of turbidities of sea waters. Besides, aerial color of a submerged object, which registers the maximum depth of discriminating such color from color of sea water, is quite similar to color of sea water itself.

1. Introductin

In recent years, the attempts of obtaining information on submerged objects by means of the remote sensing the wavelength destributions as well as the intensities of light returned back out of the sea into the air were carried on with the aid of satellites and aeroplanes. For example, LAURS *et al.*(1984) and STRETTA(1988) intended not only to determine the quantities of tuna resources in fishing grounds off the coast of California and the west coast of Africa as well but also to monitor the life and growth of coral reefs along the east coast of Australia by way of processing the image transmitted from a satellite.

The problems required to be solved in advance of developing of this remote sensing system and

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putting it in practical use can be classified into such three items as follows, (1) What is the relation between underwater physical structures including suspended substance distributions and upward radiance distributions in the area near the surface ? (2) How to make correction of an attenuation amount of each beam having a different wavelength while it is transmitted from the sea surface to a satellite or aeroplane? (3) Technology of image processing for a variety of information obtained through the detector on the satellite or aeroplane. Lately the requirements of Item 2 and 3 mentioned above have been developed fairly well so that the remote sensing system of the temperture distribution of the sea surface has been succeeded to put it to practical use. The requirement of Item 1, however, have been considerably delayed in progress.

With respect to the relation between the chlorophyll concentration in the water just below the surface and the upward spectral radiance in the area near the surface, GORDON *et al.*(1983) and KIM *et al.* (1980) introduced their own equations based on the data acquired by the water color scanner (CZCS, Coastal Zone Color Scanner; OCS, Ocean Color Scanner) of Satellite NIMBUS 7 and Space Shuttle as $C=1.13\ (L_{443}/L_{550})^{-1.71}$ ($C<1.5\mathrm{mg\ m^{-3}}$) and $C=3.26\ (L_{520}/L_{550})^{-2.439}$ ($C>1.5\mathrm{mg\ m^{-3}}$); and $C=5\exp(-5.44R)$, respectively, where C stood for the quantity of chlorophyll; L_{443}, L_{482}, L_{520}, L_{550}, and L_{552} denoted the upward radiances of which wavelength were 443, 482, 520, 550, and 552nm, respectively; and R indicated the formalized radiance differential such as $R=(L_{482}-L_{552})/(L_{482}+L_{552})$. However, even if these equations are applied to the circumstances in the different oceanic waters, the results brought about may not be satisfactory enough to justfy the relations among C, L and R. It seems to be such a reason that the quality and quantity of suspended sediments as well as plankton considerably vary with localities. VERTUCCI and LIKENS (1989) surveyed a lake in Adirondack Mountain to grasp an acidified extent of the water and collected a number of measurements in respect to the reflected spectral irradiance on the lake surface and the parameter indicating the quality of water such as DOC (Dissolved Organic Carbon), the total amount of pigment, the turbidity, pH, etc, As a result, they could make success to classify spectral distribution modes of reflected irradiance into five typical kinds, but failed to find any acidification of water which was attributed to the correlation between the distribution mode of irradiance and the parameter.

The object of this study is to understand quantitatively marine resources and control properties of sea water through optical measurements obtained from the water just below the surface. In order to achieve such object, the following three subjects must be carefully investigated.

1. Colors of water varied with localities and the reasons why such differences in color are brought forth.
2. Chromatic shiftings of colors of submerged objects observed from a biewpoint above the surface.
3. Depth limitations of discriminating colors of submerged objects from colors of waters.

2. Method

2-1 In situ observations

On board of the T/V Seiyo-maru and the Shinyo-maru as well of Tokyo University of Fisheries, the practical observations for this study were taken place on 6 different occasions such as in June 1984, April 1985, June 1985 , June 1986, February 1987 and June 1987. The objective waters of the surveys were the interior part of Tokyo Bay, the entrance of Tokyo Bay, the Bay of Sagami and the Bay of Bengal in the Indian Ocean; where the interior part of Tokyo Bay denoted the northern region of a line connecting Futtsu with Kannonzaki, the entrance district of Tokoy Bay stood for the region between a line connecting Futtsu with Kannonzaki and a line connecting Sunosaki with Jyogashima, the Bay of Sagami designated the region extended westward from a line connecting Sunosaki with Jyogashima up to the Izu Peninsula, and the Bay of Bengal denoted the region between Lat. 9° to 12° N along the line of Long. 87 ° E. The number of observation stations throughout those regions were counted 23 in total (Fig. 1).

In those observations, the downward spectral irradiance and the upward spectral radiance in the area near the sea surface, the upward spectral radiance of submerged objects and the

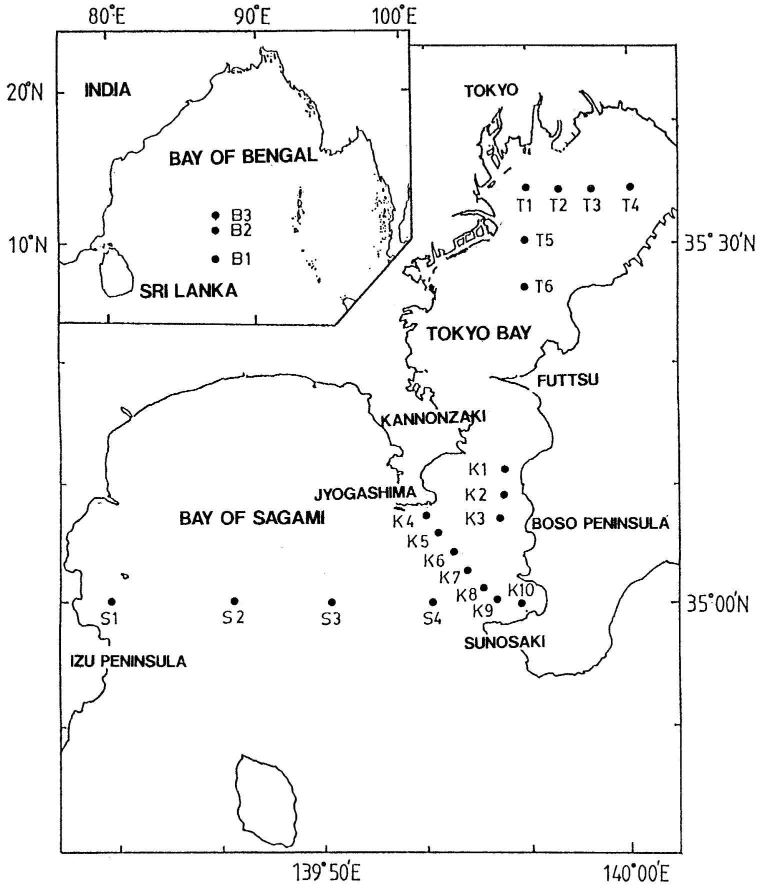

Fig. 1. Observation stations at four sea regions. The number of stations throughout those regions is counted 23 in total.

environmental factors of oceanic water are measured. For the measurements of those spectral radiances and irradiances, the Ocean Color Spectral Meter (OCSM) * was employed (KISHINO *et al.*, 1983; MATSUIKE *et al.*, 1985; FU and MORINAGA, 1988). The blue, green and red color boards made of acrylic resin, each of which had a size of 0.6m×0.6m×0.002m, were used for the submerged objects, placing each into the water of 55cm deep. The reflectances from each color plate are exhibited in Fig. 2. The dominant wavelength for each color board was 480nm for the blue, 514nm for the green and 597nm for the red one, respectively.

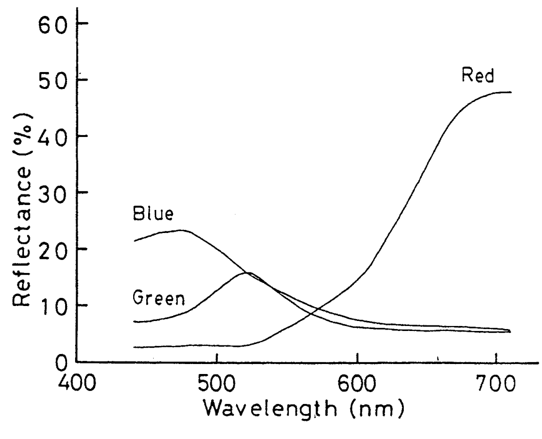

Fig. 2. Spectral reflectances from each color plate.

* Remarks: The instrument, OCSM, enables to measure the upward radiance as well as the downward irradiance of such 8 wavelengths as 440, 480, 520, 550, 600, 660, 680 and 710nm of visible lights with a high accuracy and in a short time.

Such items as turbidity, spectral irradiance, water temperature, salinity, quantity of suspended matters and particle size distributions, quantity of chlorophyll, transparency and the water color were measured as the environmental factors of sea water.

The turbidity was measured by an *in situ* Martek ligth-flux transmittance meter having an optical path length of 1 m and a dominant wavelength of 486nm. The 8 spectral submarine irradiance meter of SR–8 type manufactured by Ishikawa Sangyo was applied to measure the spectral irradiance. This instrument was used with a set of 8 interference filters providing each the respective dominant wavelength of 377, 421, 481, 513, 570, 621, 653 and 677nm for the products manufactured before the year of 1985 or 443, 481, 513, 554, 599, 664, 683 and 709nm for the ones from the year of 1986 onward. As the instruments of measuring the temperature and the salinity, S–T meter of Model 620 producted by YEOKAL Electronic's were adoptcd. The weight of suspended particles was measured by means of the filteration method (1–20/*l*) using Millipore HA Filter and the particle size distributions were resulted through Coulter Counter Model ZM of which aperture size was 100 μm. The quantity of chlorophyll contained in a certain volume of sample water was extracted by aceton after processing the water by a vacuum filteration through the glass-filter, GF/C, of Whatman, and quantitatively determined by means of the spectral light absorbancy system applying a spectral photometer. A Secchi disc, and a Forel water color meter were used to measure the transparency, and color of water, respectively.

2–2 Indoor experiment

An outline of the experimental apparatus equipped in the ladoratory is illustrated in Fig. 3.

As seen in the sketch, a cylindrical water tank of 60cm in diameter, 60cm in depth and 200 liters in volume was used for the experiment. The inside surface of the tank was coated with black paint to aboid any reflections. A projector socketed with four bulbs of Toshiba Reflector Lamp for daylight color use, of which specifications are 100V. 500W, and 5500K in color

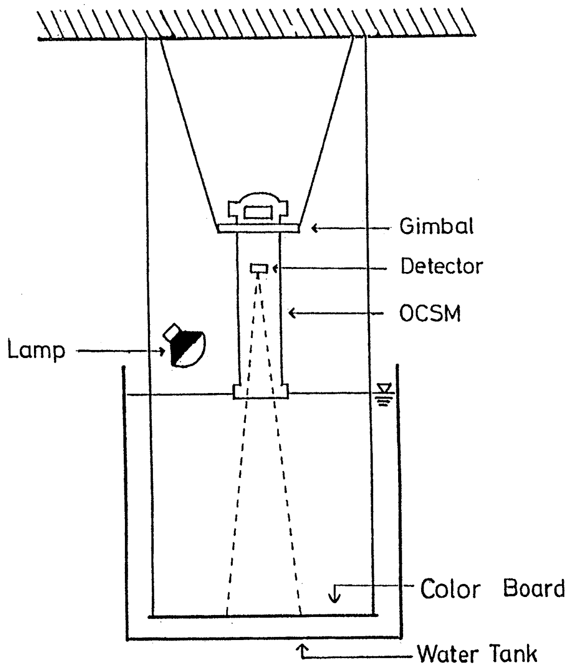

Fig. 3. Experimental apparatus.

temperature, was used for illumination, mounting it above the water tank so that the water surface could be uniformly irradiated. The tank was filled with city water strained through Millipore Filter of 1 μm in pore size so that the water have a depth of 55cm. Then, after mixing undermentioned materials with the water so as to simulate different concentrations of suspended particles, each color disc coated with the same color as used for the outdoor survey was sunken on the bottom. And, the upward spectral radiance was measurde by OCSM installed on the surface. One of clay mineral called kaolinite of which particles have an average diameter of 3.0 μm or microcystis of phytoplankton of which average particle size is 4.0 μm in diameter is used as the material to make simulative suspended particles. Such 4 different grades of kaokinite concentration as 1, 5, 10, and 50 mg/l and such 3 different grades of chlorophyll-a concentrations were applide to the indoor experiment.

2–3 Color specification

The Commission Internationale de l'Eclairage

(CIE) colorimetric system (YAMAUCHI and OMOTO, 1966) is employed for expressing colors, the color-matching functions of the energy amounts of three primary colors obtained through the human color sensation organ (i.e. human eye) are exhibited graphically in Fig.4. Such three curves shown as $\bar{x}$, $\bar{y}$, $\bar{z}$ in the graph represent each of blue, green, and red color sensation. When combined each of those $\bar{x}$, $\bar{y}$, $\bar{z}$ with the spectral energy, $E(\lambda)$, of the light, their stimulation values such as x, y, z, which are defined as "Tristimulus Values", can be interpreted as follows,

$$X=\int E(\lambda)\,\bar{x}\,d\lambda$$
$$Y=\int E(\lambda)\,\bar{y}\,d\lambda$$
$$Z=\int E(\lambda)\,\bar{z}\,d\lambda$$

If the sum (s) of tristimulus values expresses as $S=X+Y+Z$ and each value X, Y, Z is divided by S, such independent variables as $x=X/S$, $y=Y/S$, $z=Z/S$ can be found. The rectangular coodinates (x, y) established with the independent variables x, y, corresponds to a chromaticity point, and if the variable x is given on the x-axis and y is on the y-axis, the locus drawn by plotting such a point is called CIE chromaticity diagram. With reference to the quantitative expression of the color difference ($\triangle E$), it is calculated by the following equation,

$$\triangle E=600\{Y^{1/2}(\triangle S)^2+(K/600)^2[\triangle(Y^{1/2})]^2\}^{1/2}$$
where $\triangle S$ is $\{(r_1-r_2)^2+(g_1-g_2)^2+(b_1-b_2)^2\}^{1/2}$, Y is $(Y_1+Y_2)/2$, $\triangle Y^{1/2}$ is $Y_1^{1/2}-Y_2^{1/2}$ and K is 100, respectively.

3. Results

3-1 Colors of sea waters vary with different sea regions

Each of four modes in Fig. 5 shows the upward spectral radiance distributions in the area near the surface of the different sea regions; that is to say, mode(A) exhibits those at 3 points from Stn. B1 to B3 in the Bay of Bengal, mode(B) indecates those at 4 points from Stn. S1 to S4, mode(C) gives those at 6 points from Stn. K1 to K9 in the entarance of Tokyo Bay, and mode(D) illustrates those at 6 points from Stn. T1 to T6 in the interior part of Tokyo Bay.

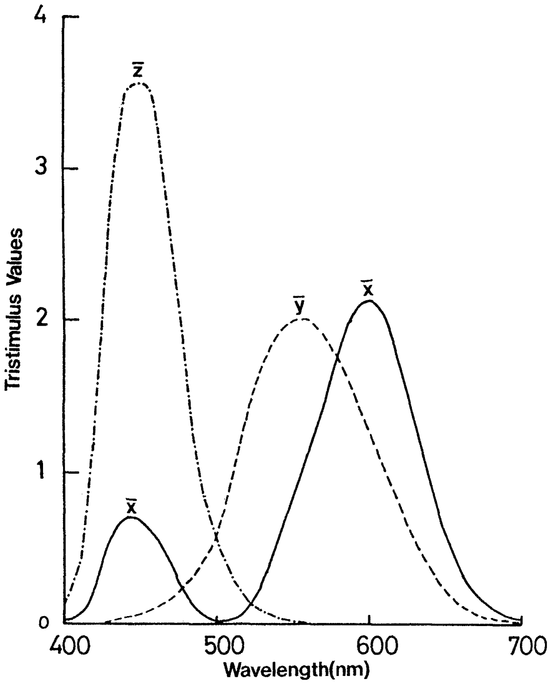

Fig. 4. CIE color-matching functions. The solid line for the values of x, the broken for y, and the one point chain for z.

The upward spectral radiance distributions in the area near the surface vary with the light intensities projected into the sea. Every practical measurement, thererfore, is required to be converted into the value of the upward spectral radiance given under the conditions of a constant light quantity reached on the sea surface. Accordingly, every value of the upward spectral radiance used in the graph of Fig. 5 is the modified one obtained by means of dividing practical measurement by the downward spectral irradiance. The relevant equation for the conversion is $Rw(0,\lambda)=Lu(0,\lambda)/Ed(0,\lambda)$, where $Lu(0,\lambda)$ and $Ed(0,\lambda)$ denote each of the upward radiance and the downward irradiance in the area near the surface, and λ stands for the wavelength. On the other hand, the environmental factors such as the turbidity, the dried weight of suspended matters, the concentration of chlorophyll a, and the transparency resulted from the investigation in those different sea regions are listed in Table 1.

It comes to be known from Figures and Table described above that the upward spectral

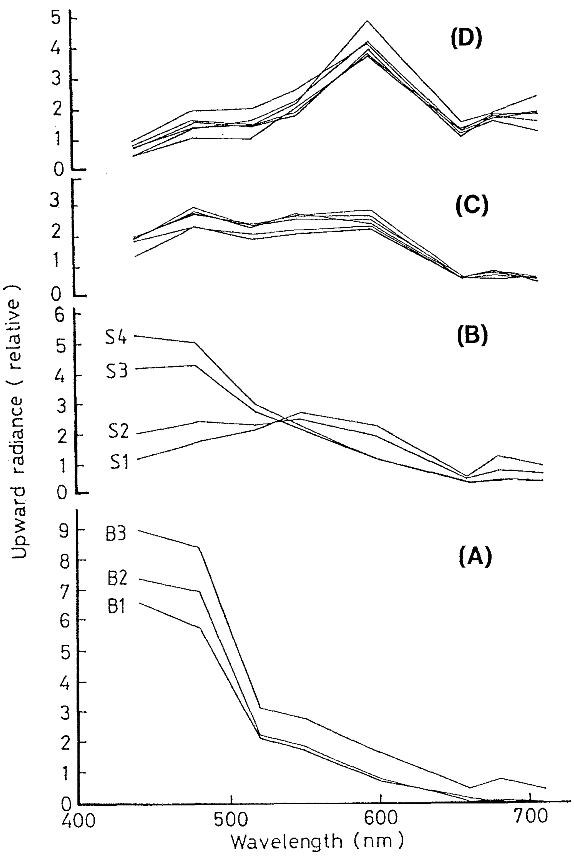

Fig. 5. Upward spectral radiance distributions at each sea region.
(A): Bay of Bengal (B): Bay of Sagami (C): Entrance district of Tokyo Bay (D): Interior part of Tokyo Bay

radiance distributions and the environmental factors distinctly vary with localities.

Sea water in the Bay of Bengal is so clear as to show its transparency of 33m and dried waight of suspended matters to be 0.21 mg/l. So far as this ocean district is concerned, the shorter wavelengths the light has the more upward spectral radiance distributions it shows (refer to mode(A)); In fact, the relative values of upward spectral radiance show such a conspicuosly high level as approximately 6 to 9 for the wavelength of 440nm to 480nm, but they exhibit a sharp or sudden declination for the wavelength of 480nm to 520nm while they show a moderate declination for the wavelengths of 520nm to 600nm, and they generally go down to zero, or show sometimes a local maximnm for the longer wavelength band than 660nm.

In the Bay of Sagami (refer to mode(B)), the nearer the positions shift towardes the Boso peninsula, the larger value of upward spectral radiance they show, and those value gradually reduces, in contrast, according to the longer band of wavelengths; but, at the positions located nearer to the Izu Peninsula, those values become smaller in the field of the shorter wavelength side of an assuming boundary considered for the wavelength of 520nm and increase, in contrast, in the field of the longer wavelength side of the boundary, and exhibit a local maximum for the wavelength of 680nm. Let us examine more in detail for the upward spectral radiance distribution at Stn. 3 located almost in a center of the Bay of Sagami. In this locality, the shorter wavelengths the light has more upward radiance for the wavelength band from 480nm decrease almost linearly and those for the longer band than do not change, keeping almost a constant level; the value at 660nm is more or less 1/25 of the largest value shown at 440nm.

The upward radiance distribution in the entrance district of Tokyo Bay shows, in contrast

Table 1. The values of turbidity, chlorophyll *a*, suspended matter and transparency at four sea regions.

Index / Sea Region	Beam Attenuation Coefficient (m^{-1})	Chlorophll *a* ($\mu g/l$)	Suspended Matter (mg/l)	Transparency (m)
Bay of Bengal (Stn. B3)	0.11	0.041	0.20	33
Bay of Sagami (Stn. S3)	0.33	0.623	1.76	20
Entrance District of Tokyo Bay (Stn. K2)	1.43	5.27	2.00	6.5
Interior Part of Tokyo Bay (Stn. T1)	4.61	49.0	10.8	1.7

to the regions mentioned above, very low values for the shorter wavelength band, and maintains an almost constant distribution of which value is approximately 2 for the wide wavelength band between 440nm and 600nm (refer to mode (C)). Furthermore, the upward rediance distribution in the interior part of Tokyo Bay, of which water is considerably muddy indicating a transparency of only 1.7m and the dried weight of suspended matters to be 10.8 mg/l, shows the larger values for the shorter wavelength band, and there is a local maximum for the wavelength of 600nm (refer to mode(D)). That is to say, the values of upward radiance distribution decrease for the shorter wavelength band less than 550nm but increase for the longer wavelength and more than 550nm, indicating an exact opposite distribution mode to that in the sea region of the Bay of Bengal.

A mode of upward radiance distribution of a sea region, which is different from that of other sea regions, comes out as a specific color of water of the sea region which is different from that of the other regions. In other words, a certain color of a sea region is a reflex of a specific mode of upward radiance distribution of the sea region. People generally say that the sea is clean or beautiful when they can see blue color of the sea. They say, however, the sea is muddy when they see the sea of green to brown colors of which wavelengths are fairly longer. The CIE colorimetric system is employed to indicate quantitatively a variety of colors of the sea. A CIE chromaticity diagram* is exhibited in Fig.6, in which colors in each sea region of the Bay of Bengal, the Bay of Sagami, the entrance district of Tokyo Bay, and the interior part of Tokyo Bay are illustrated. The nomenclatures of the sea colors at each representative observation station of those sea regions listed in Table 1 are called as "dark Purplish Blue", "dark Blue", "dusky Olive Green", and "dark Olive", and their dominant wavelengths are 474,480,554, and 580nm, respectively.

* Remarks: A visible range of upward spectral radiance applied to the chromaticity calculation for preparing of the CIE diagram are obtained the values for the wavelengths of every 10nm by means of the Lagrange's interpolation formula through Fig. 5.

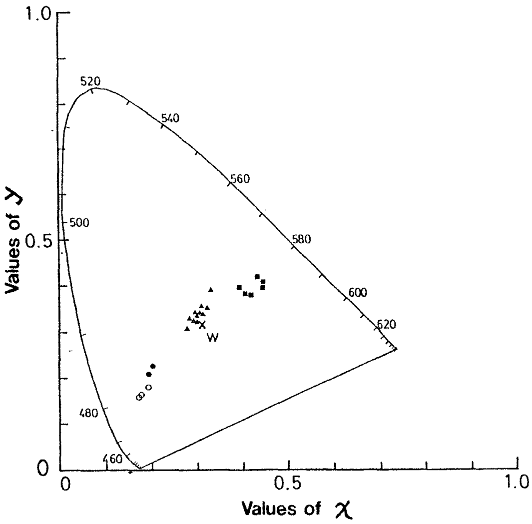

Fig. 6. CIE chromaticity diagram. The open circles for the Bay of Bengal, the solid circles for the Bay of Sagami, the triangles for the entrance of Tokyo Bay, the rectangles for the interior, and symbol W for white point.

3-2 Relations between colors of the sea water and quantities of suspended substances

The relations between colors of the sea and quantities of suspended substances are going to be discussed in this Chapter. The dried weights of suspended matters, the quantities of chlorophyll *a*, and the degrees of turbidities of water are selected as the indexes of representing the quantities of suspended substances. Each relation between the dominant wavelengths for colors of sea waters and each of the dried weights of suspended matters, the quantities of chlorophyll *a*, and the degrees of turbidities in the aforementioned 4 different sea regions is exhibited in each diagram of Figs. 7, 8, & 9, respectively; where the vertical axis of each diagram shows one of the dried weights of suspended matters, the quantities of chlorophyll *a*, and the degrees of turbidities, respectively. It comes to be learned through those diagrams that every sea region has a close but different correlation between the dominant wavelengths of colors of the sea and each of the indexes mentioned above. For example, the dried weights of suspended matters vary with the sea regions, exhibiting 0.28 in the Bay of Bengal and the Bay of Sagami 0.02 in the entrance district of Tokyo Bay, and

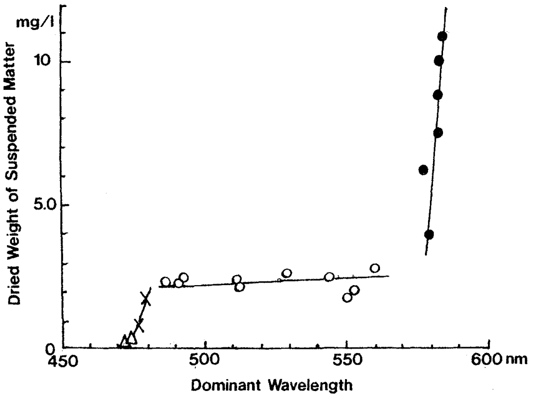

Fig. 7. Relation between the dominant wavelengths for colors of sea waters and the dried weight of suspended matter. The triangles for the Bay of Bengal, the crosses for the Bay of Sagami, the open circles for the entrance of Tokyo Bay, and the solid circles for the interior of Tokyo Bay.

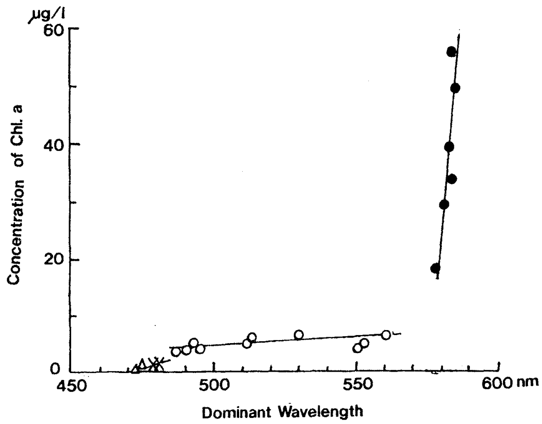

Fig. 8. Relation between the dominant wavelengths for colors of sea waters and the quantities of chrolophyll a. The symbols are same as in Fig. 7.

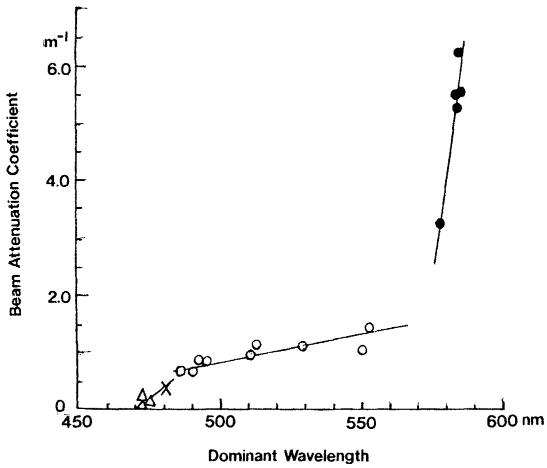

Fig. 9. Relation between the dominant wavelenghts for colors of sea waters and the degrees of turbidities. The symbols are same as in Fig. 8.

0.74 in the interior part of Tokyo Bay.

The suspended matters, in general, consist of organic and inorganic substances. As described in the preceding Chapter, the absorptions by organic substances suspended in water vary with the wavelengths of underwater spectral lights, but inorganic substances do not absorb any light. Both the organic and the inorganic substances, however, would scatter underwater lights without relating to any wavelengths. Accordingly, the relation between colors of the sea and the quantities of organic suspended substances is different from the relation between colors of the sea and quantities of inorganic suspended substances. To confirm quantitatively such a difference, a series of experiments are conducted by the use of chlorophyl a as an organic substances and kaolinite as an inorganic substances in the laboratory. Thus, the relations between wavelengths exhibited on the horizontal axis and relative upward radiances in the area near the surface given on the vertical axis under different concentrations of kaolinite and chlorophll a are shown in a diagram of Fig.10. As seen in this figure, the values of upward radiances for allover wavelengths under the 50 mg/l concentration of kaolinite as the inorganic substance almost 9 times as much as those in the case of clean filtrated water without any suspended substances. The upward radiances under the 285 μg/l concentration of chlorophyll a as the organic substance abruptly decrease their values for the shorter wavelength band less than 520nm. A CIE chromatictity diagram to show the relations between colors of the waters and both organic and inorganic suspended substane is shown in Fig.11. In the course of examining those diagrams, it is learned with interest that there is a wide difference between the upward radiance distributions in the water suspended with inorganic substances and those in the water

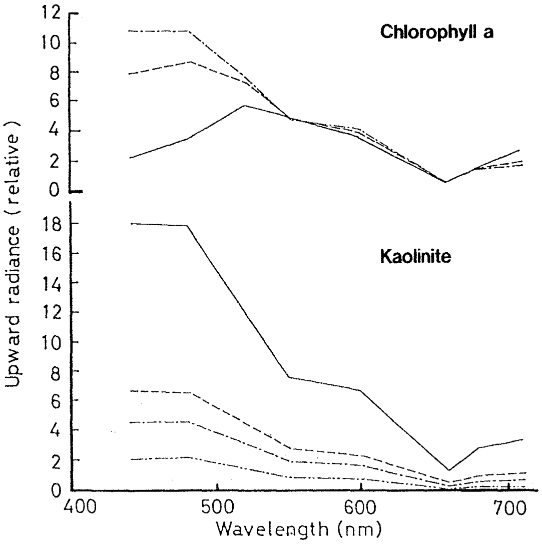

Fig. 10. Upward spectral radiance distributions under different concentrations of kaolinite and chlorophyll *a*. Kaolinite: The solid line for filtered sea water, the broken for 5mg/*l*, the one point chain for 10mg/*l* and the 2 point chain for 50mg/*l*. Chlorophyll *a*: The solid line for 285 μg/*l*, broken for 45 μg/*l*, and the one point chain for 3.5 μg/*l*.

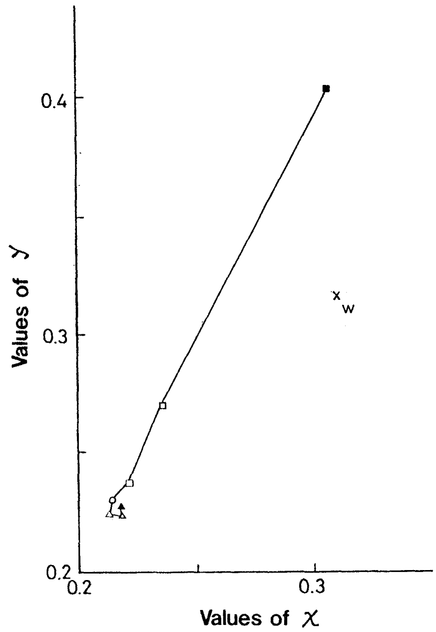

Fig. 11. Relation between colors of the waters and both organic and inorganic suspended substances shown in CIE chromaticity diagram. The open circles for filltered sea water, the triangles for inorganic substance, the rectangles for the organic substance, and symbol W for white point.

suspended with organic substances; that, in case of the water suspended with inorganic substances, colors of the waters do not change at all (dominant wavelengths: 478→476nm) even if increasing their concentration; that, under such circumstances that the water is suspended with organic substances, colors of the waters make a great change with their concentration (dominant wavelengths: 478→549nm). It can be analogically interpreted through these results of the experiments that organic suspended substances exert more influence on colors of the sea than any inorganic substances.

3-3 Chromatic shiftings of colors of submerged objects observed adove the sea surface

Colors of any objects submerged into sea water when observed from a viewpoint above the surface can be considered to vary with colors of water themselves and submerged depths of water as well.

Fig.12 shows colors of the colored boards submerged at the depth of 55cm in the Bay of Bengal and the entrance district as well as the

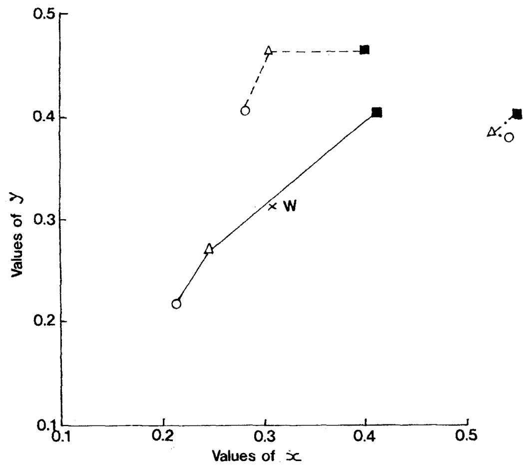

Fig. 12. Chromatic shiftings of colors of the colored boards submerged at the depth of 55cm in each sea region. Symbols ○, △ and ■ show the color of board, blue, breen, and red, respectively. The solid line for Bay of Bengal, the broken for the entrance of Tokyo Bay, and the one point chain for the interior part of Tokyo Bay.

interior part of Tokyo Bay, in which sea water colors are considerably different one another. It can be confirmed through the diagram of Fig.12 that an original color of each colored board submerged in a depth of 55cm is orderly shifted to the different colors according to the chromatic effects of different sea waters. That is to say, the diagram shows that a blue board submerged in the Bay of Bengal is seen with color of "dusky Purplish Blue" (dominant wavelength: 476nm) in terms of the chromatic nomenclature, and this color shifts to "dusky Olive" (dominant wavelength: 579nm) in the interior part of Tokyo Bay; similarly, "very dark Green" (529nm) of a green board to "dark Olive" (570nm), and " dark Yellowish Brown" (595nm) to "dark Green Brown" (591nm); besides, if the original color of the submerged board belongs to one of shorter wavelengths, it shifts to one of colors of the longer wavelenghts, and an original color of the submerged board belongs to one of the longer wavelengths, it shifts to one of shorter wavelengths, and all those colors converge in the proximity of "dark Olive" (dominant wavelength: 570nm to 582nm). This suggests that such chromatic shiftings has a certain relation with turbidities of water.

A series of experiments were conducted in the laboratory to quantitatively confirm the chromatic shiftings more in detail for the object submerged into the depth of 55cm in turbid waters having different consentrations of inorganic substances and organic substance as well. Fig.13 shows how underwater colors of different colored discs vary with turbidities of waters, where the solid line stands for inorganic suspended substances and the broken line denotes organic suspended substances. As seen, in case of the water suspended with inorganic substances, all the colors of every submerged colored disc converge into "dark Blue" in terms of the chromatic nomenclature. In case of the water suspended with oranic substances, underwater colors of the blue and the green colored disc shift toward colors of the longer wavelength band, and underwater color of the red colored disc shifts slightly towards color of one of shorter wavelength band, and all these colors seems to converge into "Yellow". In consequence, it is understood that chromatic shiftings of underwater colors for any submerged objects observed from a viewpoint above the sea surface vary with not only the properties of oubstances which cause turbidities of water but also the mixing ratios of organic substances to inorganic substances.

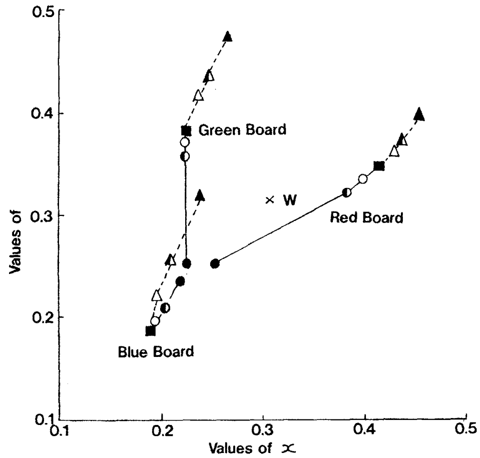

Fig. 13. Chromatic shiftings of colors of the colored boards in turbid water having different concentrations of organic and inorganic substances. The solid line for inorganic substance, the broken for organic substance, and when submerged into a depth of 55cm.

In the next place, chromatic shiftings of underwater colors with the depths of sea water are examined. Because of insuperable difficulties to solve this problem by in-situ surveys or experiments in the laboratory, it is intended, as a solution, to induce an arithmetic formula which enables to obtain theoretically underwater colors of submerged objects. For this purpuse, the study is developed by the use of the irradiance instead of the radiance in the following discussions.

It is assumed that the upward spectral irradiance, $Eu(0, \lambda)$, in the area near the surface of a colored board when it is submerged in a depth, Z, can be expressed by the sum of the irradiance, $Eub(0, \lambda)$, originated by the reflection from the colored and the irradiance, $Euw(0, \lambda)$, originated by the scattering from the water, as shown by the following equation

$$Eu(0, \lambda) = Eub(0, \lambda) + Euw(0, \lambda) \quad \cdots\cdots\cdots (1)$$

$Eub(0, \lambda)$ of the first term of the equation (1) is expressed as follows,

$$Eub(0,\lambda)=Ed(0,\lambda)\cdot Rb(\lambda)\cdot\exp[-2\cdot K(\lambda)\cdot Z] \quad \cdots\cdots(2)$$

where *Ed* (0, λ) stands for the downward spectral irradiance just under the sea surface, *Rb* (λ) for the spectral reflectance of the submerged colored board, *K*(λ) for the irradiance attenuation coeffecient, *Z* for the depth of sea water, and λ for the wavelength. The irradiance, *Euw* (0, λ), in the second term of the equation (1) is the one by substracting the upward irradiance, *Euw*(*z*–∞, λ), brought from the deeper water than the depth of z, in which the board is located, *Euw*(0–∞, λ) under conditions of not existing any board. The irradiances, *Euw*(0–∞, λ) and *Euw*(*z*–∞, λ), can be expressed as follows,

$$Euw(0-\infty,\lambda)=Ed(0,\lambda)\cdot Rw(\lambda),$$

where *Rw*(λ) denotes the irradiance radio.

$$Euw(z-\infty,\lambda)=Ed(0,\lambda)Rw(\lambda)\exp[-2\cdot K(\lambda)\cdot z]$$

But, since *Euw*(0, λ) is equal to *Euw*(0–∞, λ)–*Euw*(*z*–∞, λ),

$$Euw(0,\lambda) \text{ will be } Ed(0,\lambda)\cdot Rw(\lambda)\cdot[1-\exp[-2\cdot K(\lambda)\cdot Z]] \quad \cdots\cdots(3)$$

Subsequently, if the equations (2) and (3) are substituted into the equation (1), *Eu*(0, λ) will be equal to

$$Ed(0,\lambda)\cdot Rb(\lambda)\cdot\exp[-2\cdot K(\lambda)\cdot Z]+Ed(0,\lambda)\cdot Rw(\lambda)[1-\exp[-2\cdot K(\lambda)\cdot Z]] \quad \cdots\cdots(4)$$

The chromatic shiftings of colors of the colored boards submerged in a depth of 55cm, which are induced by aid of the equation (4) are exhibited in Fig.14. It should be noted here that the variable, *Rb*(λ), stands for the relative values of reflectances shown in Fig.2 and the variable, *Rw*(λ), denotes those of upward spectral radiances; that, taking an illustration of a case for the wavelength of 440nm, the attenuation coefficients of irradiances are $0.037m^{-1}$ in the Bay of Bengal and $2.14m^{-1}$ in the interior part of Tokyo Bay; that the solid line stands for the chromatic shifting of the blue board, the broken line for the green board, and the one point chain

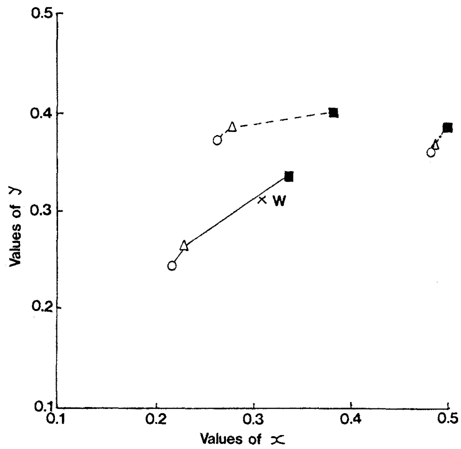

Fig. 14. Chromatic shiftings of colors of the colored boards submerged in a depth of 55cm through numerical computation. The symbols are same as in Fig. 12.

line for the red board; and each symbol such as ○, △ and ■ represents the Bay of Bengal, the entrance district of Tokyo Bay, and its interior part, respectively. It can be learned through the diagram that colors of the blue and green board shift towards the longer wavelength band while those of red board slightly shifts towards the shorter wavelength band as the depth increases, and they finally converge into "dark Yellowish Brown" (dominant wavelengths: 582 to 589nm). It may be worth describing that the results induced from the aforementioned assumption almost coincide with every practical measurement of different sea regions introduced in Fig.12. Therefore, the equation (4) is reasonable enough to use it for the computing a fairly good approximation of chromatic shiftings of colors of any submerged objects.

3-4 Depth limitations of discriminating colors of submerged objects from colors of sea water

Chromatic shiftings of colors of submerged objects caused by colors or turbidities of sea waters themselves, which are observed from a viewpoint outside the sea surface, having been discussed in the preceding chapter. In this chapter, however, the limits in depth of sea water, within which solors of the submerged board could be discriminated from colors of waters themselves when observed from a viewpoint above the surface are going to be discussed. In order to accomplish the purpuse, it is needed to recognize the human eye's threshold of color stimulus as an instrument of color sensation within which a color difference, $\triangle E$, between two colors can be discriminated one after another. The capacity of color difference of a secchi disc, of which complete dispersion body has the reflectance of 82%, in a certain depth is regarded as the threshold of color stimulus in this study. For example, the value of color difference, $\triangle E$, in the Bay of Bengal which had a transparency of 33m was 639 and that, in the interior part of Tokyo Bay which had a transparency of only 1.7m was 207, respectively.

Based on the way of thinking mentioned above, the depth limitations of color discrimination for each blue, green, and red board are obtained as 13.4m, 12.0m, and 9.1m in the Bay of Bengal of which water has a turbidity of $0.15m^{-1}$, and as 0.9m, 0.8m, and 1.0m in the interior part of Tokyo Bay of which has a turbidity of more than $4.6m^{-1}$, respectively. It may be said therefore, that such depth limitations substantially vary with different turbidities, and the depths of discrimination shows its maximum value when the color of board holds an excellent approximation to color of sea water.

4. Discussion

A typical mode of upward radiance distribution for each of 4 different sea regions stated before is selected and put together in a diagram of Fig.15 so that the characteristics of upward radiance distributions in those regions can be more clearly understood, where the solid line shows the upward radiance distribution mode in the Bay of Bengal; the broken line denotes that in the Bay of Sagami; the one point chain line indicates that in the entrance district of Tokyo Bay; and the two point chain line stands for that in the interior part of Tokyo Bay. The differences in the upward radiance distribution modes among those localities are caused by the different optical properties of those sea waters. In the course of discussing the colors of the sea, optical properties can be divided into such manners as the absorption and scattering by sea water itself, those by the suspended matters and the absorption by the dissolved organic substances. Since the scattering by water itself is inverse to

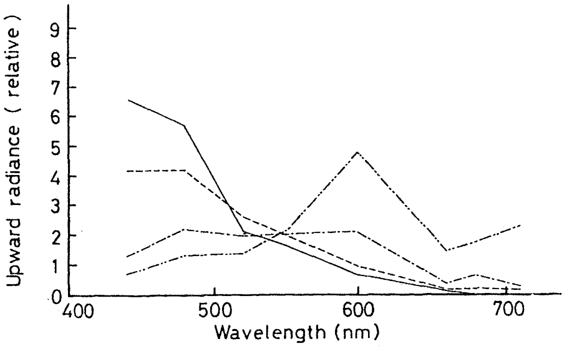

Fig. 15. Typical modes of upward radiance distribution. The solid line for the Bay of Bengal, the broken for the Bay of Sagami, the one point chain for the entarnce district of Tokyo Bay, and the 2 point chain for the interior part of Tokyo Bay.

the fourth power of the wavelength, it shows the very high walues for the shorter wavelength band. The scattering by the suspended matters, is almost constant for the shorter as well as the longer wavelength band, and the scattering coefficient is in proportion to the total cross-sectional area. The absorption by water itself shows the larger values for the longer wavelength band while the absorption by the suspended matters and dissolved organic substances exhibits the very high values for the shorter wavelength band. (JERLOV, 1976).

Since the optical property of sea water in each region can be considered as integration of the outcomes described above, the different modes of upward radiance distribution among those different sea regions are examined more in detail as started below. In case of the sea region of the Bay of Bengal of which water is very clear, the scattering of light by water itself, therefore, are carried on extensively so that its upward radiance for the shorter wavelength band shows the exceptionally high value compared with those of other sea regions. In other sea regions, however, due to turbidities increasing in order of the Bay of Sagami, the absorption of lights having shorter wavelengths by suspended matters and dissolved substances is so intensive that the upward radiance distributions may abruptly decrease. As seen in the diagram of Fig.8, the upward radiance distribution shows high values for the wavelengths of more or less 600nm in the sea region like Tokyo Bay in

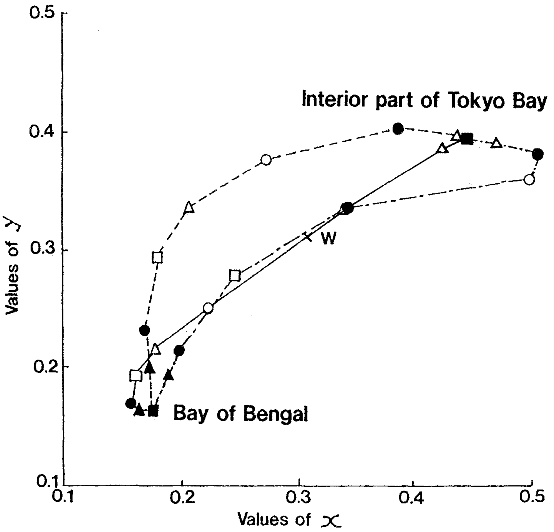

Fig. 16. Chromatic shiftings of colors of the colored boards in different depths through the computation. The solid line for the blue colored board, the broken for the green, and the one point chain for the red.

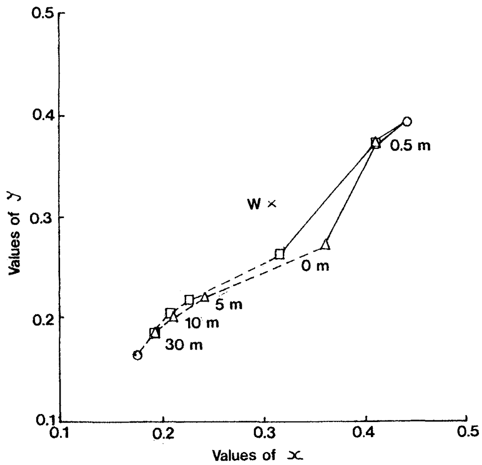

Fig. 17. Chromatic shiftings of colors of tuna's body in different depths. The broken line for the Bay of Bengal, and the solid for the interior part of Tokyo Bay. Two open circles stand for the colors of sea water in two sea regions. Symbols △ and □ show the color of yellow-fin tuna's body, and that of bigeye tuna's body, respectively.

which water is muddy enough. This is considered to be caused by the scattering developed with the increased quantities of suspended particles. As a result, it can be said through the discussion described above that the optical property of each sea region clearly attributes to the peculiar mode of the upward radiance distribution in the area near the surface.

KINNEY *et al.* (1967) introduced a study on visibility of colors of submerged objects in different sea regions. They reported that chromatic shifting of color of an object submerged in water of the Thames is quite different from that in the Gulf of Mexico; that a wide shifting in wavelengths of colors was taken place in the muddy water of the Thames while it was slight in the clean water of the Gulf of Mexico. It acquires an interest that the results of their study coincide with the authors' views.

Fig.16 shows the chromatic shiftings of colors of each submerged board obtained through the computation by aid of equation (4). For example, in case of the Bay of Bengal, each aerial dominant wavelength of which the blue, the green, and the red board is 480, 514, and 597nm will shift 477, 483, and 478nm, respectively, when each is submerged in the depth of 20m. Furthermore, the chromatic shifting rates of colors of blue board vary with its submerged depths of water, and such rates in the Bay of Bengal are larger than those in the interior part of Tokyo Bay. In consequence, it can be understood that aerial color of the board gradually shifts to color of sea water itself as the depth of water increases.

It draws interest that the those values of depth limitations of discriminating colors resulted from the study herein coincide with the practical measurements obtained by KINNEY *et al.* (1967, 1969). They practically observed the submerged the submerged different-colored targets. As a result, they could visually recognized that such a color order as yellow, blue, green, orange, and red in the clear water shifted to such an order as yellow, orange, red, green,and blue in the muddy water.

In the course of the subject discussing in this section, it may be worth considering the depth limitation of color discrimination for the body of fish instead of the colored board. Tuna species are selected as objects for the study (MORINAGA *et al.*, 1990). Based on the spectral reflected radiances of tuna measured soon after the catch in the sea region of the Bay of Bengal, the distribution of those measurements in relation to their wavelengths are examined in such way that, as for big-eye tuna, said radiances keep almost constant for allover the wavelengths except a range of 520nm to 550nm in which they have a minimum distribution; that for yellow-fin tuna, they show a minimum distribution also in the range of 520nm to 550nm, anf increase their distributions for the longer wavelength band than 550n, exhibiting a local maximum for 660nm of which degree is approximately 2 or 3 times as much as the distribution for 550nm. The color of yellow-fin tuna's body is found to be "very dusky Red Purple" (comple mentary wavelenght:501nm) in terms of chromatic nomenclature, and that of big-eye tuna's body is to be "Purplish Black"(complementary wavelength: 543nm).

Fig.17 shows how to shift colors of tuna's body in relation with depths and turbidities of water. As seen in the diagram, chromatic shiftings of colors of tuna's body vary with depths and turbidties, and like the case of the colored board mentioned above, they come similar to respective water color of each sea region as the depth of water increases. The depth limitations of disrimimating color of tuna's body from color of water in different sea regions are obtained, by the same way as the case of the colored board, as 6.1m in the Bay of Bengal and 0.5m in the inteior part of Tokyo Bay. Tha values of such limitations are widely different one another in localities, but they are little different in species of tuna.

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References

FU, K. and T. MORINAGA(1988): Correlations of upward spectral radiance near the sea surface and turbidity of water in Tokyo Bay. J. Tokyo Univ. of Fish., **75**(2), 201–212.

GORDON, H. R., D. CLARK, J. W. BROWN, O. B. BROWN, R. H. EVANS, and W. BROENKOW (1983): Phytoplankton pigment concentrations in the Middle Atlantic Bigth; comparison of ship determinations and CZCS estimates. Applied Optics, **22**, 20–36.

JERLOV, N. G. (1976): Marine optics. Elsevier Scientific Publ. Comp. Amsterdam.

KIM, H. H., C. R. MCCLAIN, L. R. BLAINE, W. D. HART, L. P. ATKINSON and J. A. YODER (1980): Ocean chlorophyll studies from a U-2 aircraft platform. J. Geophys. Res., **85**, 3982–3990.

KINNEY, J. A. S., S. M. LURIA and D. O. WEITZMAN (1967): Visibility of colors underwater. J. Opt. Soc. Am. **57**(6), 802–809.

KINNEY, J. A. S., S. M. LURIA and D. O. WEITZMAN (1969): Visibility of colors underwater using artificial illumination. J. Opt. Soc. Am. **59**(5), 624–628.

KISHINO, M., S. SUGIHARA and N. OKAMI (1983): Ocean color spectrum meter (OCSM) for remote sensing study. J. Remote Sensing Soc. Japan, **3**(2), 13–20.

LAURS, R. M., P. M. FIEDLER and D. R. MONTGOMERY (1984): Albacore tuna catch distributions relative to environmental features observed from satellites. Deep-Sea Res., **31**, 1085–1099.

MATSUIKE, K., T. MORINAGA and T. MIYAZAWA (1985): Studies in oceanic remote sensing I. The relationship between upward spectral radiance near the sea surface and the suspended matter quantity, quality and existing depth. J. Tokyo Univ. of Fish., **72**(2), 111–125. (in Japanese).

MORINAGA, T., T. KOIKE and K. MATUIKE (1990): Underwater visibility of a vranch line of longline gear to tuna in the bay of Bengal. La mer, **28**(2/3), 117–122. (in Japanese).

The Illuminating Engineering Institute of Japan (1987): Measurements of light. Nihonriko shhupankai (in Japanese).

STRETTA, J. M. (1988): Forecasting tuma fisheries area: what parameters, what models? The praxeological response. The second French Japanese Symposium of Oceanography, Shimizu. Japan.

VERTUCCI, F. A. and G. E. LIKENS (1989): Spectral refoectance and water quality of Adirondack mountain region lakes. Limnol. Oceanogr., **34** (8), 1656–1672.

YAMAGUCHI, J. and G. OMOTO (1966): Handbook of color science. Association of color science, Nankodo (in Japanese).

海面上から見た水中物体の色

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要旨：海中資源量の把握と水質管理を海面上の光学的物理量の測定より行うことを目的として，海の色の海域による相違とその原因，海面上から見た水中物体の色の移動，及び水中物体の色と海の色との判別水深を，海洋の現場観測と室内実験の双方から解析した。

(1) ＣＩＥ表色系による海の色名はベンガル湾で「dark purplish blue(主波長：474nm)」，相模湾で「dark blue(480nm)」，東京湾口部で「dusky olive green (554n)」及び東京湾奥部で「dark olive(580nm)」である。このように海の色は海域によって異なり，その相違は主に海中の有機懸濁物量の差に起因していると言える。

(2) 海面上から見た水中色彩板の色は水深や海水の濁り（懸濁物や溶存物に起因する）で変化する。例えば，清澄な海水（濁度：$0.11m^{-1}$）のベンガル湾の水中 20m 深では，空中で青色（主波長：480 nm），緑色（514nm)及び赤色（597nm）を呈する色彩板の各色は477,483及び478nmの各主波長の色に移動する。深度が増大して，究極的にはベンガル湾の海の色（474nm）自身に収束する。

(3) 上記の色彩板の各色（空中）と海の色との差を肉眼で判別する限界水深は，清澄な海水のベンガル湾でそれぞれ 13.4, 12.0 及び 9.1m，濁った海水（濁度：$>4.6m^{-1}$）の東京湾奥部でそれぞれ 0.9, 0.8 及び 1.0m である。

(4) 海面上から見て水中物体を視認し得る深さは，物体の色や海水の濁りで大きく異なる。又，その判別水深の最大値を示す物体の色（空中）は海の色に類似した色彩である。