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The Optical Characteristics of the Water in the Three Oceans Part—IV*

An Attempt to the Approximate Figures of Seasonal Solar Energy reached to and penetrated in the Water of the Three Oceans

Kanau MATSUIKE**, Tsutomu MORINAGA** and Tadayoshi SASAKI***

Abstract: An attempt to the approximate figures of seasonal distribution of solar energy reached to and penetrated in the water of the oceans, as a preliminary step to the estimation of primary production in the oceans from the optical point, was performed in the Indian Ocean, North Pacific Ocean and Antarctic Ocean on the same lines in the part III. In consequence, the total amount of solar energy for the year in each depth showed marked differences in each zone of the oceans as illustrated in Fig. 5. By way of example, it could be said that underwater solar energy already came to 33.4 Kg·cal/cm^2·year in 10 m deep in the equator of Indian Ocean and was 54 % of that, in the Kuroshio region of the North Pacific Ocean, 44 % in the Sub-Antarctic zone, 13 % in the Antarctic zone and 6 % in the Antarctic Convergence zone, respectively.

Besides, on the assumption that a lower limit of the photic zone is marked by the depth where underwater surface solar energy is reduced to 1 % or 5 g·cal/cm^2·day, the ratio of the total photic zone for the year in unit area of sea surface was approximately 100 : 80 : 60 : 25 or 100 : 75 : 50 : 20 in the equator of the Indian Ocean, Kuroshio region, Sub-Antarctic zone, and Antarctic and Antarctic Convergence zones, respectively.

1. Introduction

The solar insolation on the ocean may be considered fairly different to that of the continent, and moreover, the optical nature of water-mass in the same or different oceans is distinguished in terms of spectral transmittance of downward irradiance. So, we dealt with the estimation of solar energy reached to and penetrated in the water of the oceans by depth and zone as regard to consistent process from sky to underwater.

In previous paper, light transmittance of the air (q) was calculated from solar constant in consideration of its seasonal change and solar insolation reached to the water surface, and the relation between q and the solar altitude in clear sky, the relations between q and the solar altitude in various kinds of cloud in front of the sun, and the relation between cloud amount and reduction ratio of solar insolation were studied. Besides, the distribution of underwater solar energy in the summer of the oceans was estimated in studying the underwater optical characteristics in the oceans.

In this paper, we calculated the possible solar insolation in both hemispheres from Lat. 65°S to Lat. 65°N on the oceans, the average amount of solar insolation on the sea surface basing on that value, and distributions of underwater solar energy by depth and season for the year in each zone of the Indian, North Pacific and Antarctic Ocean by using above-mentioned relations.

In connection with the studies on possible solar insolation, the estimated values were proposed by UKRAINTSEV (1939), MATEER (1955), GAVRILOVA (1958, 1963), etc. Ukraintsev's was that of the north hemisphere, which was calculated from the formula, being formed of total hours of daylight and coefficient concerning

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** Tokyo University of Fisheries
*** Tokyo University of Fisheries, The Institute of Physical and Chemical Research

to year and latitude, obtained due to disposing the data of the observatory located in the continent from Lat. 35°N to Lat. 70°N, and Mateer's and Gavrilova's were of the area of Lat. 50°N and northward centering the Arctic.

Various published empirical formulae were indicated by many authors concerning to solar insolation, and the reduction ratio of solar insolation indicated a rectilineal change to the increase of cloud amount in many cases, as being represented by KIMBALL (1928). In recent year, ALBRECHT (1958), ASHBURN (1963) demonstrated the complex formulae as a function of various parameters.

As regard to the distribution of underwater solar energy, there were SASAKI *et al.* (1958), JERLOV (1964, 1968), etc., as mentioned in previous paper, but not many.

2. Possible solar insolation from Lat. 65°S to Lat. 65°N on the oceans

In previous paper, we described the relation between q and solar altitude in clear sky by using Fourier formula in consideration of the fact that the change of q in clear sky is regarded only to solar altitude with a view to be ignored the influence of position, vapour or moisture, and dust, etc. on q in the atmosphere on the ocean, because the relation showed a smooth distribution curve besides the range of dispersion was small in disregard to the differences of observating position and date.

So, in this paper, possible solar insolation in both hemispheres from Lat. 65°S to Lat. 65°N on the oceans was calculated by the following equation.

$$S_0=2\,I_0\int_{a=0}^{a=90-(l\pm d)}\{1-(0.371\sin a+0.225\sin 3a+0.0842\sin 5a+0.0443\sin 7a+0.0250\sin 9a\ldots)\}^{\operatorname{cosec} a}\,da$$

S_0: possible solar insolation
I_0: solar constant
a: solar altitude
l: latitude
d: declination of the sun
$90-(l\pm d)$: the altitude of meridian pass of the sun

The result was shown in Fig. 1-(a) and (b) or Table 1. It should be said that possible solar insolation in the summer made little dif-

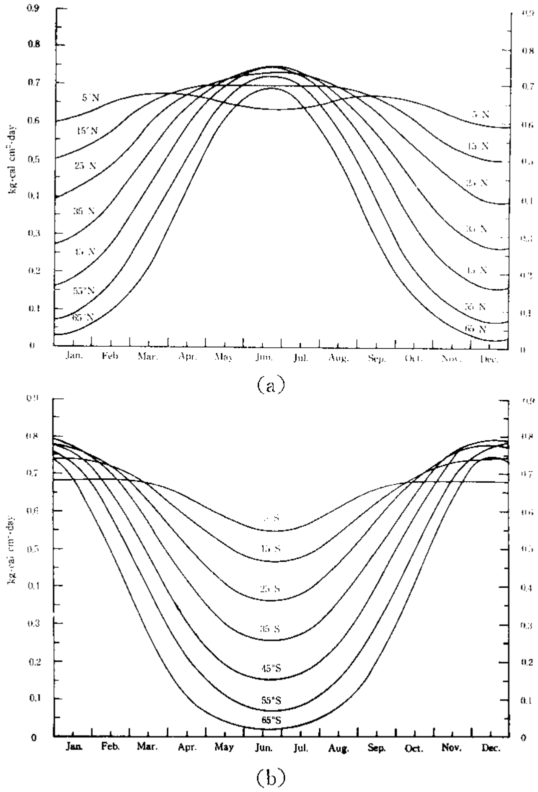

Fig. 1-(a) and (b). The distribution of possible solar insolation in both hemispheres by month and latitude.
(a): in the northern hemisphere
(b): in the southern hemisphere

ference due to disparity of latitude, and the nearer to the winter, the larger become the the differences of possible solar insolation by latitude.

UKRAINTSEV (1939) showed possible solar insolation in northern hemisphere by month and latitude, though it was pointed out by BUDYKO (1956) that his value was too large. In comparing with his consequential value to that of northern hemisphere in this paper, Ukraintsev's was about 10 % larger in each latitude almost in parallel than that of ours. MATEER (1955), GAVRILOVA (1963) also took into account possible solar insolation of Lat. 50°N and northward centering the Arctic by the method similar to Ukraintsev's. As compared their values to those of this paper, both are partly the same but the remainder is 2~3 % greater than our values.

Table 1.

Possible solar insolation in the northern hemisphere

Month \ Lat.	5°N	15°N	25°N	35°N	45°N	55°N	65°N
Jan.	0.61	0.51	0.41	0.29	0.18	0.09	0.04
Feb.	0.65	0.58	0.49	0.39	0.28	0.17	0.09
Mar.	0.67	0.65	0.59	0.52	0.43	0.33	0.22
Apr.	0.67	0.69	0.67	0.64	0.59	0.51	0.43
May	0.65	0.70	0.71	0.72	0.70	0.66	0.61
Jun.	0.64	0.70	0.73	0.74	0.74	0.72	0.69
Jul.	0.64	0.70	0.73	0.73	0.72	0.70	0.65
Aug.	0.66	0.69	0.69	0.67	0.63	0.57	0.50
Sep.	0.67	0.67	0.62	0.57	0.50	0.40	0.30
Oct.	0.66	0.61	0.54	0.44	0.34	0.23	0.14
Nov.	0.62	0.53	0.45	0.33	0.21	0.11	0.05
Dec.	0.59	0.50	0.39	0.27	0.16	0.07	0.03

Kg·cal/cm²·day

Possible solar insolation in the southern hemisphere

Month \ Lat.	5°S	15°S	25°S	35°S	45°S	55°S	65°S
Jan.	0.68	0.74	0.77	0.78	0.76	0.73	0.69
Feb.	0.68	0.72	0.72	0.70	0.65	0.59	0.49
Mar.	0.68	0.67	0.63	0.57	0.49	0.39	0.28
Apr.	0.64	0.58	0.51	0.42	0.31	0.21	0.10
May	0.59	0.51	0.41	0.30	0.19	0.11	0.04
Jun.	0.55	0.47	0.36	0.26	0.15	0.07	0.03
Jul.	0.56	0.48	0.38	0.27	0.17	0.08	0.03
Aug.	0.61	0.55	0.46	0.36	0.25	0.16	0.08
Sep.	0.66	0.62	0.58	0.50	0.41	0.30	0.21
Oct.	0.68	0.69	0.68	0.64	0.58	0.50	0.40
Nov.	0.68	0.73	0.75	0.75	0.74	0.68	0.63
Dec.	0.68	0.74	0.77	0.79	0.79	0.77	0.75

Kg·cal/cm²·day

ASHBURN (1963) presented the results of measurements of the solar and the total net irradiance at ocean station PAPA (Lat. 50°N, Long. 145°W) during two years of 1960 and 1961, and the correlation coefficient between the mean monthly global solar irradiance and the mean monthly cloudiness. As compared with his mean values in clear sky to that of Lat. 50°N in this paper, it can be said that the both are almost coincident.

3. Solar insolation on the sea surface of the oceans

Solar insolation on the sea surface in each zone of the Indian (A~H zone), North Pacific (I~L zone) and Antarctic (M~P zone) Oceans were calculated throughout the year by using the following formula conducted from the relation between the reduction ratio of solar insolation and cloud amount in previous paper:

$$S=S_0(1-0.026\,C^{1.3})\ ,$$

where S, S_0 and C are solar insolation on the sea surface, possible solar insolation and cloud amount.

The used data of the distribution of cloud amount in each zone of the oceans were quoted from U. S. Navy Marine Climatic Atlas of the World, Vol. II, III, VII, which are statistically compiled from sources for 5~90 years in Vol. II, North Pacific Ocean, and Vol. III, Indian Ocean, and for 10 years in Vol. VII, Antarctic Ocean.

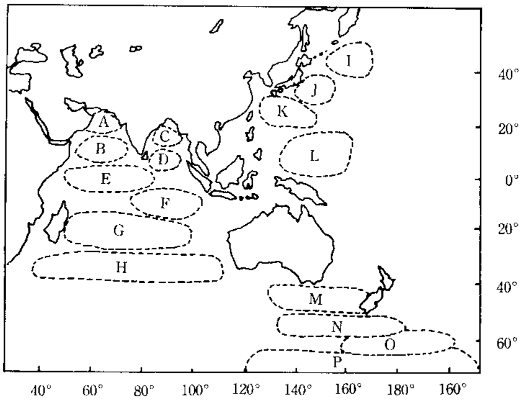

Fig. 2. Each zone of the oceans.
Remark: Dotted line denotes area of the zone.

In Fig. 2, the three oceans were divided into 16 areas, symbolized with A~P for convenience' sake.

The results of computations of solar insolation on the oceans in all seasons are illustrated in Fig. 3. It appears that the seasonal change of solar insolation is complicated due to weather in such zones faced on the continent as the Arabian Sea and Bay of Bengal.

Comparing the values in Lat. 10°S, Long. 72°~171°E presented by KIMBALL (1928) to ours, where is overlapped area, the former is a little larger than the latter in August and September, both the same in July, and smaller in other months within disparity less than 10 %. Moreover, it should be pointed out that the values in Lat. 50°N, Long. 145°W proposed by ASHBURN (1963) and in Lat. 45°~70°S, Long. 132°E~149°W showed in Atlas Antrktiki almost coincide with ours.

Computing detailed values of the solar insolation in hemisphere based upon various listed formulae, the results are fairly different from each other. Further work will be necessary to determine the precision of the measurements and to develop an equation expressing the solar insolation received at the ocean surface.

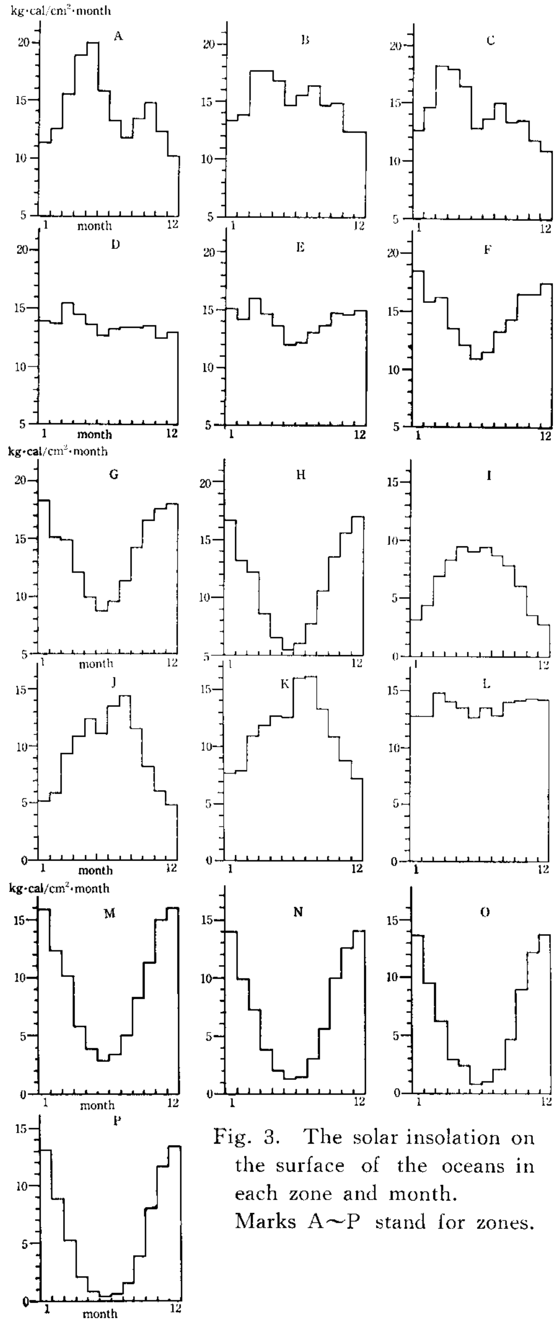

Fig. 3. The solar insolation on the surface of the oceans in each zone and month.
Marks A~P stand for zones.

4. Distribution of underwater solar energy

Before entering into the estimation of underwater solar energy, reflected amounts of solar energy at the sea surface in all seasons were calculated with the aid of the results quoted from COX and MUNK (1955) on an occasion of cloudy weather, and from ANDERSON (1954) in cloudless, in due consideration of sea condition data cited from U. S. Navy Marine Climatic Atlas of the World.

In a series of the papers, it was pointed out that the underwater optical nature in terms of

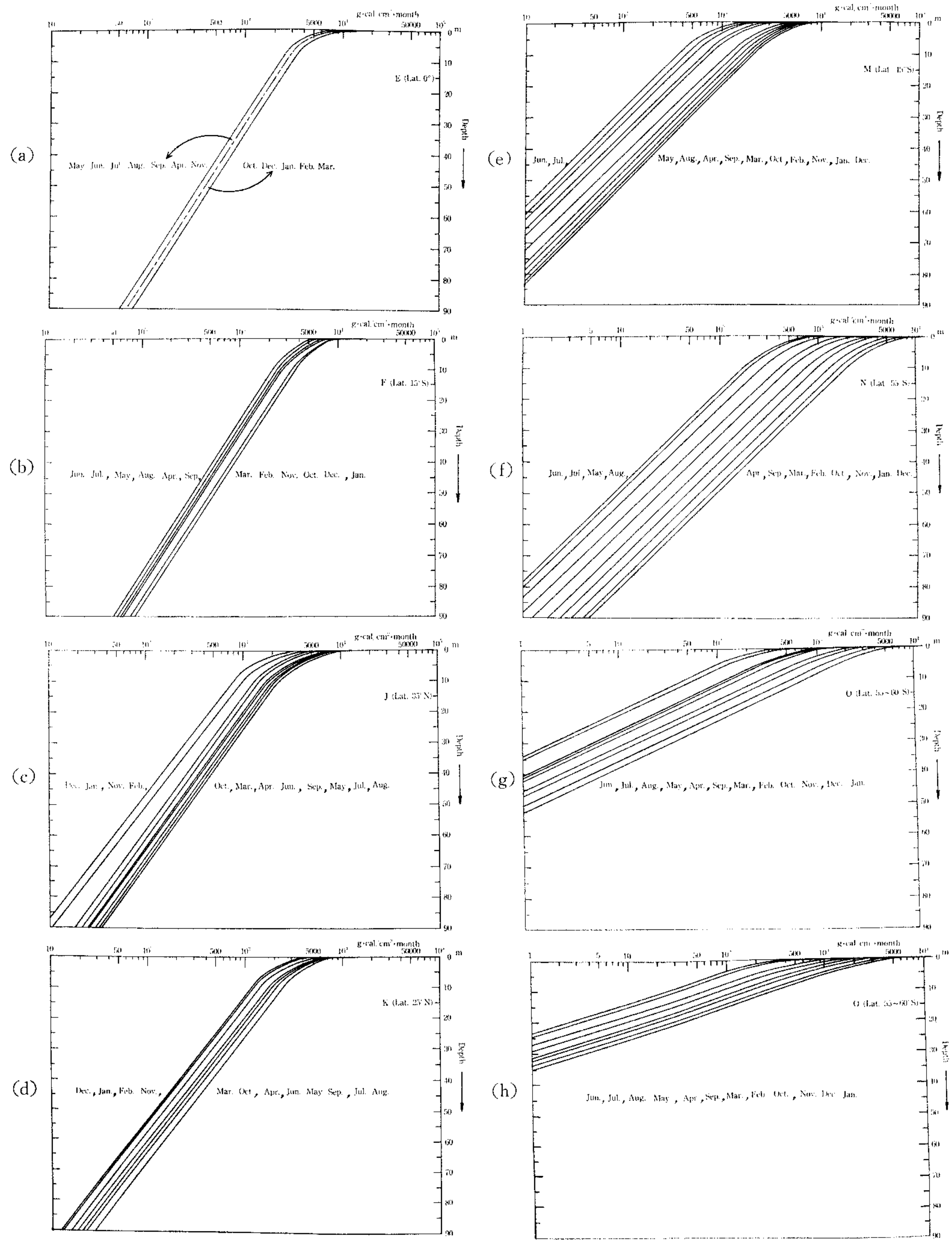

Fig. 4 (a)~(h). The distribution of underwater solar energy by depth in each zone and month.

spectral transmittance in each zone of the oceans showed fairly different modes, and the distinct differences in the distribution of underwater solar energy were noticed through those characteristics.

The estimation of underwater solar energy by depth in all seasons was performed by applying the method mentioned in the previous paper in due consideration of requiring the very similar type in each zone by comparing our data obtained from the Indian, North Pacific and Antarctic oceans to those of Jerlov's which made optical classification of oceanic and coastal waters and calculation of percentage of total irradiance from the sun and sky by layer.

A series of figures (Fig. 4-a~h) show the distribution of underwater solar energy by depth in each month and zone of the Indian, North Pacific and Antarctic oceans.

As intended to estimate simply the total amount of underwater solar energy by depth for the year in each zone, it was illustrated in Fig. 5.

This allows records through these figures concerning to the ratio of the total amount for the year in each zone of the oceans on an average as shown in Table 2.

The total amount of solar energy for the year in each depth showed marked differences in each zone of the oceans, and by way of example, it could be said that underwater solar energy already came to 2 Kg·cal/cm^2·year in 10 m deep in the Antarctic Convergence zone which was 1/17 of that in the equator of the Indian Ocean and 1/9 in the Kuroshio, besides, that in the Kuroshio was 1/2 in the equator of the Indian Ocean on an average and this ratio tended to increase more with the depth going deeper.

The question arises whether the distribution of underwater solar energy by depth could be indicative of the distribution of oceanic productivity in the view of the optical point.

RYTHER (1956, 1959), ARUGA and MONSI (1962), etc. emphasized the facts concerning to the relation between light intensity and photosynthetic activity, and the changes of the characteristics of photosynthesis in accordance with the depth.

On the assumption that a lower limit of the photic zone is marked by the depth where underwater surface solar energy reduced to 1 % or

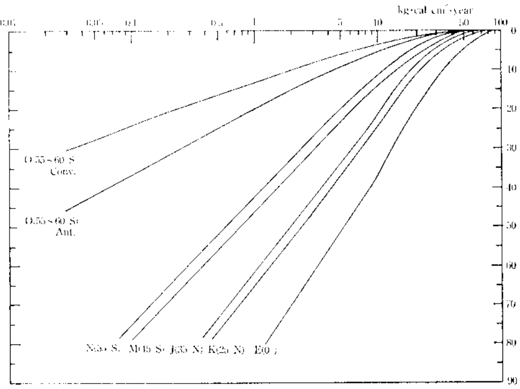

Fig. 5. The distribution of the total amount of underwater solar energy for the year by depth in each zone.
Signs Ant. and Conv. stand for the Antarctic and Antarctic Convergence zones.

Table 2. The ratio of the total amount of underwater solar energy for the year by depth in each zone.

Layer \ Area	Indian Ocean		Kuroshio region	Sub-Ant. Ocean	Ant. Ocean Lat. 55~60°S	
	Total	Lat. 0°	Lat. 35°N	Lat. 45°S	Ant.	Conv.
Meter	Kg·cal/cm^2·year	Ratio	Ratio	Ratio	Ratio	Ratio
0	160.7	100 %	67 %	65 %	46 %	46 %
1	70.9	100	65	62	39	35
5	46.6	100	59	52	23	15
10	33.4	100	54	44	13	6
25	17.8	100	46	25	3	0.5
50	5.3	100	36	14	0.3	
100	0.45	100	24	5		

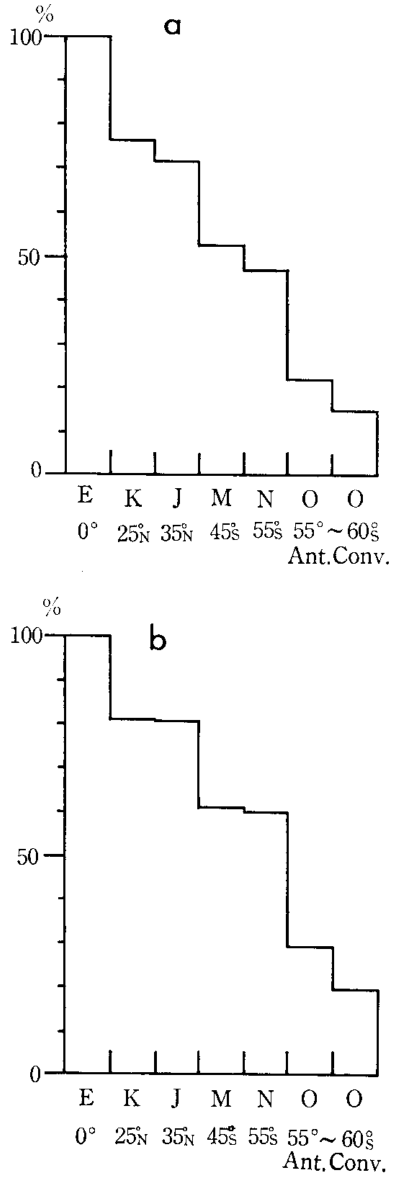

Fig. 6-(a) and (b). The ratio of the total volume in unit area of sea surface which is marked by the depth where underwater solar energy reduce to 1% (a) or 5 g·cal/cm^2·day (b).
Signs Ant. and Conv. stand for the Antarctic and Antarctic Convergence zones.

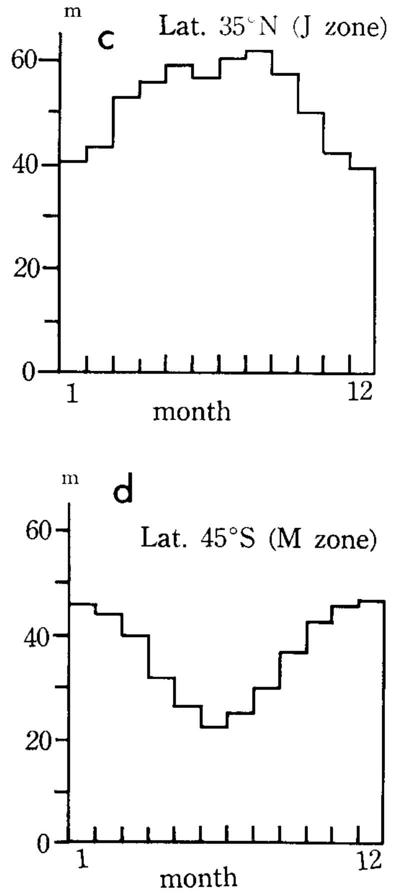

Fig. 6-(c) and (d). The monthly mean depth where solar energy penetrate more than 5 g·cal/cm^2·day in the Kuroshio (c) and Sub-Antarctic (d) zones.

5 g·cal/cm^2·day, the ratio of the total volume of photic zone in unit area of sea surface in each zone to that in the equator of the Indian Ocean, as illustrated in Fig. 6-(a) and (b), could be said to be approximately 100:80:60:25 or 100:75:50:20 in the equator of the Indian Ocean, Kuroshio region, Sub-Antarctic zone, and Antarctic Convergence zones, respectively.

It is possible to represent the graphs of the monthly mean depth where solar energy penetrate more than 5 g·cal/cm^2·day in the zone of the Kuroshio (Lat. 35°N) and Sub-Antarctic (Lat. 45°S) as an example.

It was pointed out through these figures (Fig. 6-c, d) that there is a difference of about 20 m on mean value between summer and winter.

5. Summary and conclusion

An attempt to the approximate figures of seasonal solar energy reached to and penetrated in the water of the oceans is summarized as follows:

1) Possible solar insolation in both hemispheres from Lat. 65°S to Lat. 65°N on the ocean in all seasons was calculated and the results were shown in Fig. 1-(a) and (b) or Table 1.

2) The results of computation of the solar insolation on the sea surface of the Indian, North Pacific and Antarctic Oceans throughout the year were illustrated in Fig. 3.

3) The distribution of underwater solar energy in each zone of the oceans mentioned aboved was estimated throughout the year in due consideration of reflected amounts of solar energy at the sea surface and results were shown in Fig. 4.

4) The total amount of solar energy for the year in each depth showed marked differences in each zone of the oceans as illustrated in Fig. 5, and for example, it could be said that underwater solar energy already came to 33.4 Kg.cal/cm². year in 10 m deep in the equator of the Indian Ocean and was 54 % of that, in the Kuroshio region, 44 % in the Sub-Antarctic zone, 13 % in the Antarctic zone and 6 % in the Antarctic Convergence zone, respectively.

5) On the assumption that a lower limit of the photic zone is marked by the depth where surface solar energy is reduced to 1 % or 5 g·cal/cm²·day, the ratio of the total photic zone for the year in unit area of sea surface is approximately 100 : 80 : 60 : 25 or 100 : 75 : 50 : 20 in the equator of the Indian Ocean, Kuroshio region, Sub-Antarctic, and Antarctic and Antarctic Convergence zones, respectively.

It has been demonstrated that an attempt to the approximate figures of seasonal solar energy reached to and penetrated in the water of the oceans with a view to estimating primary production in the oceans from the optical point in future. However, these estimation includes problems awaiting solution in following aspects. The seasonal change of underwater optical characteristics is not yet studied, though it could be thought that these are not so large in the equatorial ocean due to little change of distribution of solar energy or temperature in the water but it is possible to exist fairly changes in high latitude in the northern or southern hemisphere. We could not account of these points in this work and instead, we used the underwater optical nature in the summer as the representation of whole season. Another point is that the relation between the reduction ratio of the solar insolation on the sea surface and cloud amount have fairly wide distribution due to the definition of cloud amount itself and data is not so much, and moreover, the dispersion of calculating results by the formulae presented by many authors are fairly large in each position. Accordingly, it may be added that this estimation should be better to think much of relative value or comparison in each zone and ocean. By the further studies of optical characteristics in its seasonal or daily change in the ocean and more discussions to the problems relating to solar insolation on the oceans, these estimation will increase more its accuracy.

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三大洋の海中における光学的特性—IV

三大洋における海面到達太陽エネルギー及び海中太陽エネルギー分布の季節別概算の試み

松生 洽 森永 勤 佐々木忠義

要旨 光学的面からみた大洋の生産力推定の一段階として，前報に基づいて，南北両半球の洋上における可能日射量，北太平洋，インド洋及び南極洋の各海域における海面到達日射量及び海中太陽エネルギー分布の四季別変化を概算し，各深度における年間太陽エネルギー分布を各海域別に表わした．たとえば， 10 m 深の場合，インド洋赤道海域では 33.4 Kg•cal/cm^2•year で，北太平洋黒潮海域ではその 54 %，亜南極海域では 44 %，南極海域では 13 % 及び南極収斂線海域では 6 % と言える．

更に，光学的面からみた生産力範囲を海面透入量の 1 % 又は 5 g•cal/cm^2•day 以上の太陽エネルギー量であると仮定すると，この年間総計の大洋の生産力範囲の比は，海面の単位面積について，インド洋赤道海域，北太平洋黒潮海域，亜南極海域，南極海域及び南極収斂線海域でおのおの 100 : 80 : 60 : 25 又は 100 : 75 : 50 : 20 と言える．

今後，大洋海中の光学的性質の季節的変化，及び大洋洋上における日射量のより詳しい調査により，この概算の精度をあげていかねばならない．