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Possible occurrence of anomalies in solar energy absorbed by sea water in turbid layers and shallow areas[*1]

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The effects of a high concentration of materials in upper ocean water on the absorbed solar energy were investigated by a simple optical model. The results of calculations using the irradiance attenuation coefficient classified by Jerlov[*1] show a remarkable increase in the upper limits of the turbid layer, indicating an anomaly of absorbed solar energy. In addition, the contribution of upward irradiance reflected from the sea bottom near the beach upon absorbed solar energy were investigated by a similar model. In this case, the results indicate that bottom reflection plays a rather minor role on the amounts of solar energy absorbed by sea water. This, however, implies that the energy absorbed by the bottom can act as a secondary heat source which can potentially heat the sea water just above the bottom.

1 Introduction

The light penetrating sea water is partly absorbed by various materials: the water itself, suspended matter, phytoplankton and dissolved organic matters. Since most of the light absorbed is converted to thermal energy, the thermal structure of the upper ocean layer is largely affected by irradiance distribution.

In order to predict the total downward irradiance, which refers to total energy in the whole spectrum, an exponential decrease with depth has been assumed, for example, by Denmann[2]. Although the irradiance below 10m depth is apt to obey the exponential decrease, this assumption is a poor approximation in the upper layer because of the preferential decrease in the short and long spectral regions. To improve this situation, Kraus[3] expressed the downward irradiance as a summation of two exponential terms; one term characterizes the rapid decrease of longer spectral components in the upper layer while the other term characterizes the moderate decrease in visible spectral components in the deeper layer. This expression has been accepted for approximating the general irradiance distribution.

On the other hand, if the particle rich layer is

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present in the subsurface layer, as often occurs in a middle latitude ocean, the irradiance in this layer is attenuated more than in the upper and lower layers.

In addition to this case, near the beach where the water is not very deep, sea water may expect to receive more solar energy than in deeper bottoms since the upward irradiance reflected by the bottom remains strong. In these cases, we cannot anticipate the total irradiance of the exponential decrease with depth. Further, the attenuation in the particle rich layer and reflectance from the shallow bottom accompanies a change of the spectral shape of irradiance because of selective absorption and reflection. In all these cases, the exponential difference expression for total irradiance is no more applicable than the other to predict the actual irradiance distribution.

To cope with such cases, the total irradiance calculated from spectral irradiance distribution when assuming that the exponential decrease in irradiance is valid only for a constant wavelength results in a more appropriate approximation.

Thus, the amount of solar energy absorbed in the particle rich layer is calculated in this paper by assuming the exponential decrease of irradiance at each wavelength for varying optical water types classified by Jerlov[1]. Further, absorbed solar energy in the shallow layer near the beach is calculated for varying the water depth.

2 Computational schema

Spectral irradiance falling on the sea surface, $E_{0,\lambda}$, was calculated from irradiance obseved outside the earth's atmosphere by Thekaekara[4] and the atmospheric transmittance used in the computer programme "LOWTRAN 5" by Kneizys et al.[5] as maritime extinction (23km visibility). In this case, the moving average of irradiance outside the earth's atmosphere is calculated and used since the spectral variations are too large for practical use. The calculated spectral irradiance just above the sea surface is shown in Fig.1.

The underwater downward irradiance at the wavelength of λ at the depth z, $E_{d,\lambda}(z)$, is expressed by,

$$E_{d,\lambda}(z) = \{1-R(\theta)\}\,[E_{0,\lambda}\cdot\exp\{-K_\lambda(z)\}\cdot z] \quad (1)$$

where θ, R and K are the incident angle of the sun beam, reflectance at the sea surface and irradiance

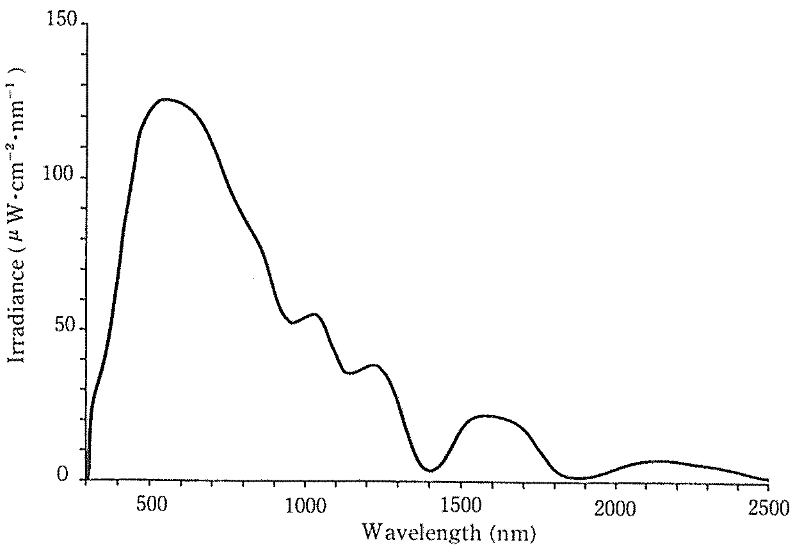

Fig.1 Calculated spectral distribution of solar energy falling on the earth's surface.

attenuation coefficient, respectively.

When the water is deep, the contribution of upward irradiance, $E_{u,\lambda}(z)$, to absorbed solar energy is negligible since the ratio of $E_{u,\lambda}(z)$ to $E_{d,\lambda}(z)$ is, in general, less than 1% in the sea around Japanese Islands as reported by Okami et al[6].

On the other hand, when the bottom depth, z', is shallow, then $E_{u,\lambda}(z)$ generated by the reflection of $E_{d,\lambda}(z')$ at the sea bottom must be taken into consideration, and expressed by

$$E_{u,\lambda}(z) = E_{d,\lambda}(z') \cdot R'_{\lambda} \cdot \exp\{-K_{\lambda}(z'-z)\} = E_{0,\lambda}\{(1-R(\theta))\} \cdot R'_{\lambda} \cdot \exp[-K_{\lambda}(z) \cdot \times \{2z'-z\}] . \quad (2)$$

An equal R'_{λ} for upward irradiance to that for downward irradiance is assumed in Eq.2. The K_{λ} for different optical types classified by Jerlov[1] is used in calculating Eq.2. For the shake of the simplicity of the computation, a normal incidence ($\theta = 0$) is assumed.

Total upward and downward irradiance in the spectral range of 300 to 2,500nm, P_d and P_u, are then calculated by,

$$P_d(z) = \int_{300}^{2500} E_{d,\lambda}(z) d\lambda, \quad \text{and} \quad (3)$$

$$P_u(z) = \int_{300}^{2500} E_{u,\lambda}(z) d\lambda. \quad (4)$$

Using Eqs.3 and 4, the irradiance was calculated at every 10nm wavelength. When $P_d(z)$ and $P_u(z)$ are given the amount of solar energy absorbed (ΔP) in a layer between $z - \Delta z/2$ and $z + \Delta z/2$ is obtained by

$$\Delta P(z) = \{P_d(z-\Delta z/2) - P_d(z+\Delta z/2)\} - \{P_u(z-\Delta z/2) - P_u(z+\Delta z/2)\}. \quad (5)$$

3 Results

3.1 Effects of a turbid layer

Formation of a maximum particle concentration has been reported by many workers who directly measured turbidity, that is, beam transmittance. For example, Okami et al.[6] found that a turbid layer with about 1m in thickness was developed from 40 to 60m in oceanic water of the central part of the Japan Sea. In the Gulf of California, a turbid layer around 20m depth and 10m or more thick was often observed by Tyler and Smith[7].

In order to investigate the effects of the particle rich layer lying between the upper and lower clearer layers upon irradiance distribution, five cases of combination water types classified by Jerlov[1] were selected and given in Table 1. IA is selected for typical clear water because waters I to IB are frequently encountered in the Kuroshio region, judging from the irradiance distribution (Okami et al.[6]).

$P_d(z)$ was calculated from Eqs.1 and 3 for Cases B and C along with Case A, and the results are shown in Fig.2. In both Case B and Case C, a remarkable decrease in the rate of irradiance was found in the high particle concentration layer. This large decreasing rate is almost equal to that around 1m depth (40 %/m). The decreasing rate in the layer between 10 and 20m for Case B and that in the layer between 20 and 30m for Case C are almost identical.

Figure 3 shows absorbed solar energy per 1m as a function of depth for Cases B and C, along with for

Table 1. Water types used in the computation

Depth	Case A	Case B	Case C	Case D	Case E
0m–10m	IA	IA	IA	IA	IA
10m–20m	IA	III	IA	3	IA
20m–30m	IA	IA	III	IA	3
30m–	IA	IA	IA	IA	IA

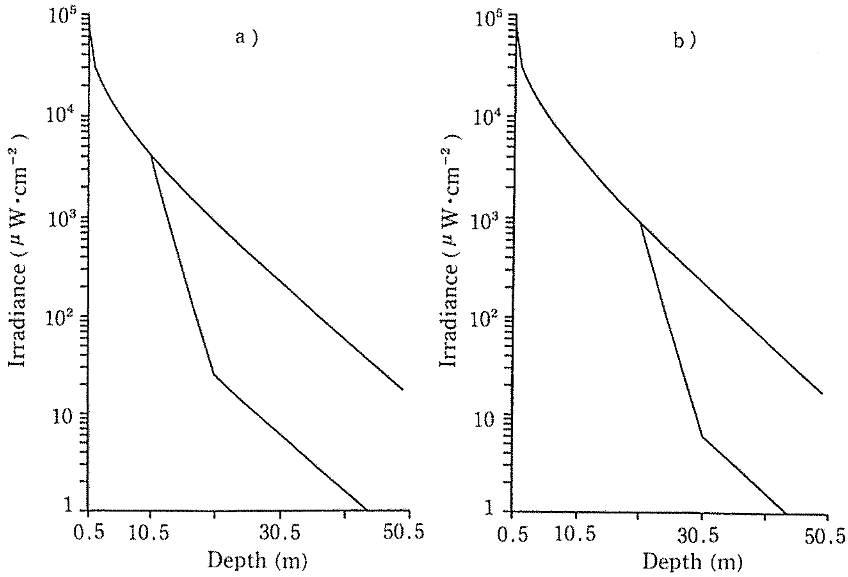

Fig.2 Calculated total irradiance as a function of depth.
a) : Cases A(upper) and B (lower), b):Cases A(upper) and C(lower).

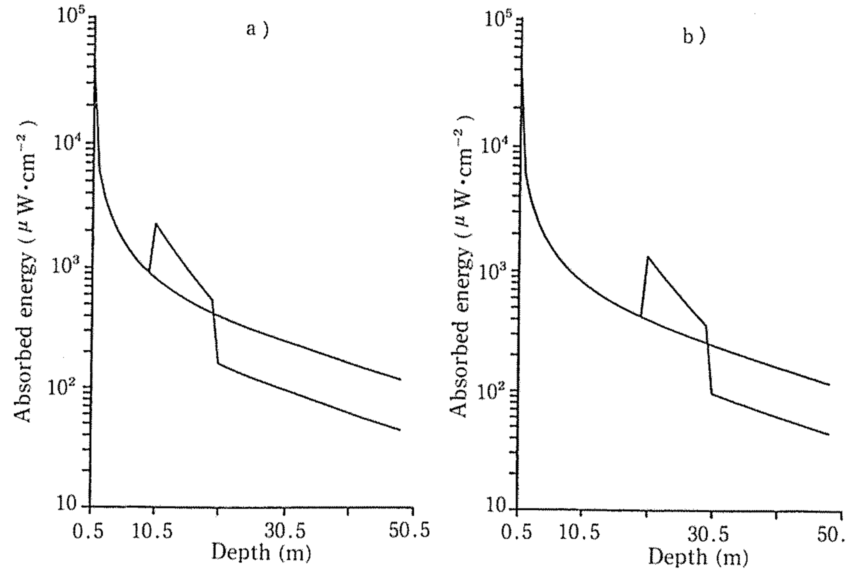

Fig.3 Solar energy absorbed by the turbid layer is compared with that in the absence of a turbid layer for Cases B and C. a) : turbid layer ranges between 10 and 20m. b) : turbid layer ranges between 20 30m.

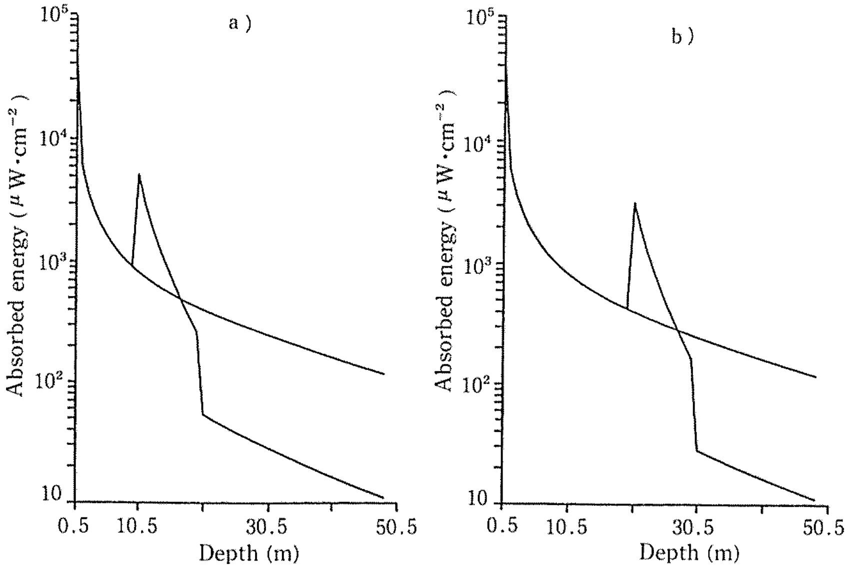

Fig.4 Solar energy absorbed by the turbid layer is compared with that in the absence of a turbid layer for Cases D and E. a) : turbid layer ranges between 10 and 20m. b) : turbid layer ranges between 20 and 30m.

Case A. An increase in absorbed solar energy is found in the turbid layer in both cases. Maxima absorbed energy for Cases B and C are 2,275 and 1,331 μW/cm², respectively, which occur at 10.5 and 20.5m, corresponding to the upper limit of the turbid layers. These values for Cases B and C are 1,459 μW/cm² and 930 μW/cm², respectively, larger than absorbed energy at the same depth for the Case A. Moreover, absorbed energy for Cases B and C even in the lower limit of the turbid layer is 30 to 40% larger than for Case A.

Fig.4 shows absorbed solar energy for Cases D and E as a function of depth along with that for Case A. Maxima for Cases D and E are 5,114 μW/cm² and 4,298 μW/cm², respectively, at the upper limit of the turbid layer, indicating the ΔP for both are about two to three times larger than those for Cases B and C, respectively. The strong absorption in the upper part of the turbid layer results in a small ΔP in the limit of the lower layer ; ΔP for Cases D and E are about 50% smaller than that at the same depth for Case A. Thus, the sharp maxima in ΔP are developed in the upper limit of the turbid layer. At the same time, a sharp decrease in absorbed energy appears between the lower limit of the turbid layer and upper limit of the clear water.

These computational results are supported by the ΔP distribution calculated from observed irradiance. Figure 5 shows the vertical distribution of absorbed solar energy computed on the basis of the irradiance data collected in Kuroshio region. The maxima in ΔP are found in the layer between 10 and 50m depth. The occurrence of these anomalies in absorbed solar energy are frequently observed in other areas of the Kuroshio region, suggesting the presence of a turbid layer.

3.2 Effects of the bottom

The absorbed solar energy near the beach where the water depth is shallow is calculated by Eq.2.

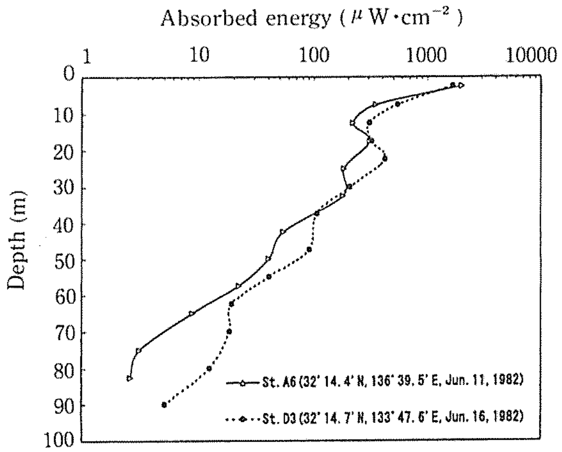

Fig 5 Solar energy absorbed by sea water is caluculated from spectral irradiance observed in the Kuroshio region.

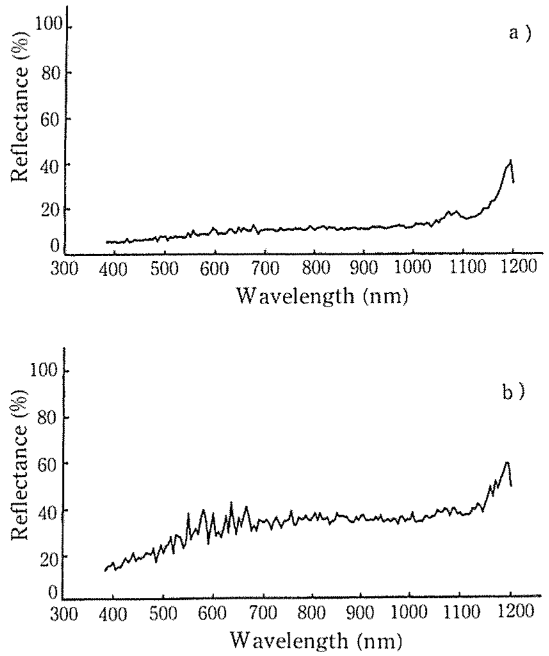

Fig 6 Wet sand reflectance collected in the Taklimakan Desert in China, supplied by Ishiyama.

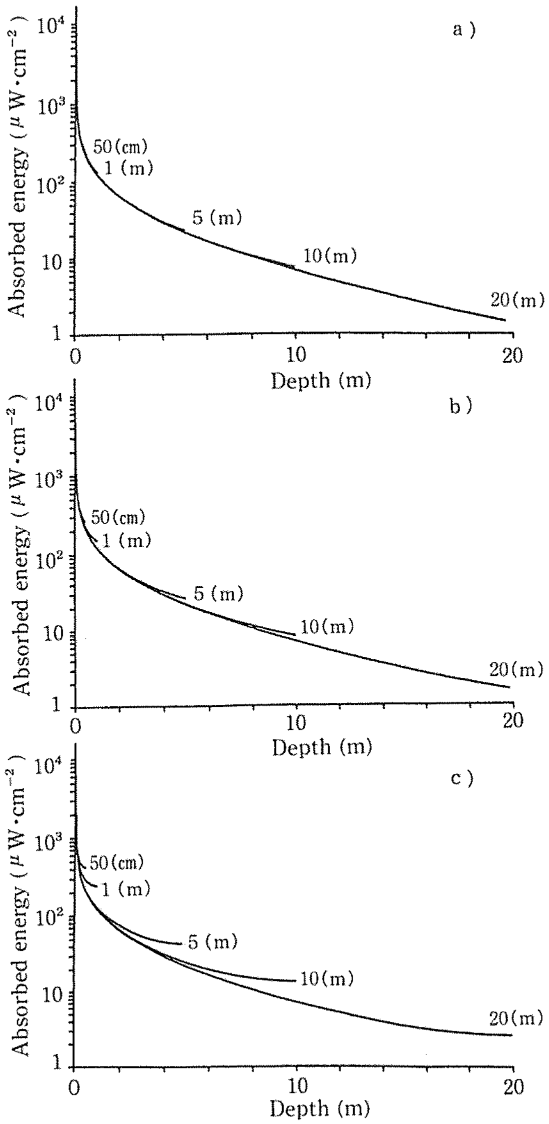

Fig 7 Solar energy absorbed by sea water near the beach varying the water depth. Numbers attached to the curves stand for the water depth.
a) : sand reflectance for sample A is used.
b) : sand reflectance for sample B is used.
c) : hypothetical sand reflectance of 100% in the whole spectral range is used.

Experimentally determined R'_λ for a wet bottom is not available in the whole spectral range of 300nm to 2,500nm as far as we know. The spectral reflectance of wet sand collected in the Taklimakan Desert in China was measured in the laboratroy by Ishiyama*. By reference to his data, the sand reflectances are available to estimate in the spectral range between 400 and 1,200nm. The spectral reflectances of samples A and B are shown in Fig.6. In the computation, unknown reflectances below 400nm and above 1,200nm are assumed to be equal to that at 400nm and 1,200nm, respectively.

Taking the reflectance of sample A, ΔP for coastal water type 1 was calculated by Eq.5 for five various bottom depths: 0.5, 1, 5, 10 and 20m. As shown in Fig 7a, the effects of bottom reflectance are found only near the bottom; the increase in absorbed solar energy is less than 10% just above the bottom layer. As shown in Fig. 6a, the R' used in this calculations is very low ; of 5 to 7% in the spectral range between 400 and 500nm. This is why there are less effects by bottom reflectance on the amount of absorbed solar energy.

Figure 7b shows the results of R' assumed for sample B. In this case, ΔP near the bottom increases up to 20% in each bottom. To investigate the bottom effect, a hypothetically large bottom reflectance of 100% in the whole spectral region was taken exaggeratedly, and the results are shown in Fig.7c.The ΔP near the bottom is two times larger than that for deep bottom depths.

Thus, if the sand reflectance is comparable with that used in this calculation, the effect of bottom reflectance upon the absorbed solar energy is at most 20% even in shallow depths near the beach. Although the sand reflectance in the desert does not differ so markedly from that in the beach, the beach sands may often include shells that have a higher reflectance than sand grains alone. In general, however, Ishiyama et al.[8] reported that reflectance decreases sharply with increasing moisture content. Accordingly, a similar result might be derived more or less even if the other reflectance data is used. However, the small reflectance leads to the absorption of residual solar energy by sands at the bottom. Accordingly, the bottom sand plays the role of heating the sea water just above the sand. This results in a similar ΔP distribution to that obtained on the assumption that the sand reflectance is 100% over the whole spectral range.

4 Discussion

The contribution of the turbid layer absorption to sea water temperature is obtainable from $\Delta P(z)$ calculated above. The temperature increase ΔT in Δt hour is related by.

$$C_p \cdot \rho \cdot \Delta T / \Delta t = \Delta P(z) / \Delta z \qquad (6)$$

where $C_p = 3.93 J/g \cdot K$ is the specific heat of sea water and $\rho = 1$ is the density of water. The increase in temperature after 1 hour is calculated. Since ΔT is virtually proportional to ΔP as shown in Eq.6, the profile of ΔT shows the same results as that for ΔP. Contributions to temperature for Cases B and C are about 0.02℃ and 0.015℃, respectively in the upper limit of the turbid layer, while in the lower limit of upper clear water, it is 0.009℃ and 0.004℃ for Cases B and C, respectively. This results in an inversion of temperature distribution. In the upper limit of lower clear water, the contrubution of solar energy to the temperature becomes significantly small (<0.0002℃) as compared with that at the lower limit of the turbid layer. This large difference serves to maintain the thermocline.

For cases D and E, the sharper maximum are developed; maxima which appear at the upper limit of the turbid layer are 0.05℃ and 0.03℃, respectively.

Thus, the temperature difference is significantly large in both upper and lower limits of the turbid layer. This acts to develop a maximum in temperature in the upper limit and a sharp thermocline in the lower limit of the turbid layer.

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5 Concluding Remarks

The foregoing discussion leads to the following conclusion. When the turbid layer is present between clearer water, as usually develops in the middle latitude region, a maximum of absorbed solar energy appears in the upper limit of the turbid layer. This refers to the occurrence of the inversion of absorbed energy in the subsurface layer. In addition, the effects of bottom reflection upon absorbed solar energy were investigated when the water depth is very shallow such as near the beach, and it was suggested that the bottom reflection plays a role to some extent on the increase in solar energy absorbed by sea water. In this case, the solar energy absorbed by the bottom can act as a secondary heat source which increases the temperature of sea water just above the bottom.

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高濁度層と浅海域の海水による太陽エネルギー吸収量の増大

吉永　聡・杉原滋彦

要旨：海中に入射した太陽エネルギーは、海中の諸物質により吸収されて、大部分が熱エネルギーに変換される。すなわち海水を暖める。海水の吸収が比較的大きいため、表層付近で多量のエネルギーが吸収され、深度の増大と共に指数関数的に減少するのが一般的である。しかし、30m付近において高濁度層が存在すると、上層よりも多量のエネルギーが吸収されることになる。また、岸近くの浅海域においては、海底からの反射光が強いため、深海域よりも多量の熱エネルギーへの変換が予想される。そこで、海水による熱エネルギーへの変換量を定量的に取り扱うため、簡単な光学模式と既存の資料を使って、各深度において吸収量を計算した。その結果、高濁度層の存在によって吸収量の逆転が起こることを示した。また、浅海域では海底の影響が予想より小さかったが、これは海底の吸収率が高いためである。しかし、このことは海底が光エネルギーを多量に吸収することであり、二次的な熱源となることを示す。