Vertical Attenuation Coefficient of Downward Irradiance in Lake Oze

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Abstract

In Lake Oze, the downward irradiance in the region 400~700 nm E_d was measured in 1987. E_d was measured at depths $z=0, 0.1, 0.3, 0.5, 1$ m, and then at 1-m intervals to 8 m. E_d at $z=0$ m was measured just below the lake surface. When the ratio of E_d to E_{d0} , which is the value of E_d at $z=0$ m, is plotted with a logarithmic scale, relation between E_d/E_{d0} and z was approximately linear. The vertical attenuation coefficient of downward irradiance K_d ranged from 0.49 to 0.85 m^{-1} .

In Lake Oze, absorption coefficient of the lake water was minimum at wave length $\lambda=570$ or 580 nm, so E_d was estimated to be maximum at $\lambda=570$ or 580 nm, and the incident direct solar radiation at $\lambda=570$ or 580 nm must reach a considerable depth. If it is assumed that the incident direct solar irradiance is mainly attenuated by absorption of the lake water, K_d depends on solar altitude and absorption coefficient. When the values of the angle of refraction and absorption coefficient at $\lambda=570$ nm are given, K_d for downward irradiance at $\lambda=570$ nm is calculated. The calculated values of K_d were in approximate agreement with those obtained from the measurement of E_d except in September.

Key words : incident direct solar irradiance, downward irradiance, solar altitude, absorption coefficient.

1. Introduction

Downward irradiances in lake waters were measured by KIRK (1977, 1981), SUGAWA (1978), ARAI (1981), WEIDEMANN and BANNISTER (1986), and vertical distributions of downward irradiances were obtained. Downward spectral irradiances in lake and sea waters were measured by SMITH *et al.* (1973), JERLOV (1976), TSUDA (1980), KISHINO *et al.* (1984), WEIDEMANN and BANNISTER (1986), and spectral distributions of downward irradiances were obtained at different depths.

Lake Oze stretches over Gunma and Fukushima Prefectures. The Ohe River, Hinoki and Wase Creeks, and other smaller creeks flow into the lake, from which the water flows out through the intake. Downward irradiance in Lake Oze was measured monthly during the

period from June to October 1987 except July. The location of the observation station is shown by an open circle in Figure 1. Vertical distribution of the ratio of downward irradiance to that just below the lake surface in each month was not equal as in Figure 2. Therefore vertical attenuation coefficient of downward irradiance K_d was also not constant. In the present study the author discusses the factors by which K_d is influenced.

2. Measurement of downward irradiance

Downward irradiance E_d was measured with LI-COR LI-192SB underwater quantum sensor for the total quantum flux in the region 400~700 nm. All measurements were carried out under sunny condition. The sensor surface was arranged horizontally and the sensor was lowered into the lake water.

Fig. 1. Lake Oze and location of observation station.

Fig. 2. Vertical distribution of E_d/E_{d0} .

Let z be the depth from the lake surface. E_d was measured at $z=0, 0.1, 0.3, 0.5, 1$ m, and then at 1-m intervals to 8 m. E_d at $z=0$ m was measured just below the lake surface. Depth of the lake bottom varied from 8.0 to 8.3 m

during the period from June to October.

Let E_{d0} be the value of E_d at $z=0$ m. Value of E_{d0} and measured time are presented in Table 1. When the ratio of E_d to E_{d0} is plotted with a logarithmic scale, the vertical distribution of E_d/E_{d0} was approximately expressed by a straight line as in Figure 2. Numerals on the straight lines represent measured months.

Vertical attenuation coefficient of downward irradiance K_d is given by

$$K_d = -\frac{d(\ln E_d)}{dz} \quad (2-1)$$

From Figure 2 and Eq. (2-1), K_d is obtained and presented in Table 1. The values of K_d ranged from 0.49 to 0.85 m^{-1} .

KIRK (1980) obtained values of K_d in lakes in Australia. The values of K_d in Lakes Burley Griffin, Ginninderra, George, and Burrinjuck and Corin Dams were 0.91~6.93, 0.84~1.99, 6.03, 0.71~0.90, and 0.87 m^{-1} , respectively. WEIDEMANN and BANNISTER (1986) also obtained values of K_d in lakes. The values of K_d in Irondequoit Bay, which is a lake discharging into Lake Ontario through a narrow and shallow outlet, and of Lakes Onondaga, Otisco, and Oneida, were 0.90~1.30, 1.22, 0.64, and 0.96 m^{-1} , respectively. The value of K_d in Lake Oze was nearly equal to that in Lake Otisco but smaller than in the other lakes.

3. Solar altitude at measured time

Solar altitude h was given by WADACHI (1979) as

$$\sin h = \sin \varphi \sin \delta + \cos \varphi \cos \delta \cos t \quad (3-1)$$

where φ , δ , and t are latitude, declination and hour angle.

The value of φ at the observation station is about $36^\circ 55'$, and δ and t are obtained from

Table 1. Values of E_{d0} , K_d , and h .

Date (1987)	Time	E_{d0} ($10^3 \mu E \cdot m^{-2} \cdot sec^{-1}$)	K_d (m^{-1})	h ($^\circ$)
22 June	14:50	1.60	0.49	47.9
24 August	15:00	1.39	0.66	39.2
29 September	8:40	1.00	0.85	31.2
13 October	9:22	1.25	0.72	36.8

measured date and time. When values of δ and t are given, h is calculated from Eq. (3-1) and presented in Table 1. The values of h ranged from 31.2 to 47.9°.

4. Spectral absorption coefficient of lake water

Spectral absorption coefficient of lake water $a_y(\lambda)$ is expressed by

$$a(\lambda) = a_y(\lambda) + a_p(\lambda) + a_w(\lambda) \quad (4-1)$$

where $a_y(\lambda)$, $a_p(\lambda)$, and $a_w(\lambda)$ are absorption coefficients at wave length λ by dissolved yellow substance, particulate matter, and pure water, respectively. Water samples were collected from $z=0, 3$, and 6 m at the observation station. Spectral transmittance with reference to distilled water $T(\lambda)$ was measured in the region $400\sim 700$ nm at 10-nm intervals by Hitachi U-3400 spectrophotometer. $a(\lambda)$ of the water sample was obtained by the following method.

Absorption by dissolved yellow substance : When the water sample is filtered through pore size $0.2 \mu\text{m}$ membrane filter, particulate matter in the water sample is removed, and attenuation of the beam passing through the filtered water with reference to distilled water is due to absorption by dissolved yellow substance. Then $a_y(\lambda)$ is expressed by

$$a_y(\lambda) = \frac{1 - T(\lambda)}{l} \quad (4-2)$$

where l is path length of glass cells, and 10 cm path length glass cells were used. Values of $a_y(\lambda)$ at 50-nm intervals are presented in Table 2.

The value of $a_y(\lambda)$ increased as the value of λ decreased. The values of $a_y(\lambda)$ in June and October increased with depth, while those at $z=3$ m in August and September were larger than at $z=0$ and 6 m.

Absorption by particulate matter : When the water sample is not filtered, part of the beam passing through the water sample is scattered. KIRK (1980) showed that the backward scattering coefficient was much smaller than the total scattering coefficient. Then backward scattering may be negligible in comparison with total scattering, and directly transmitted and for-

ward scattered beams are measured by attaching Hitachi 150 mm ϕ integrating sphere to Hitachi U-3400 spectrophotometer. When the integrating sphere is used, attenuation of the beam passing through the water sample with reference to distilled water is due to absorption by dissolved yellow substance and particulate matter. Then $a_y(\lambda) + a_p(\lambda)$ is expressed by

$$a_y(\lambda) + a_p(\lambda) = \frac{1 - T(\lambda)}{l} \quad (4-3)$$

and 5 cm path length glass cells were used. Therefore $a_p(\lambda)$ is obtained by subtracting $a_y(\lambda)$ from $a_y(\lambda) + a_p(\lambda)$. Values of $a_p(\lambda)$ at 50-nm intervals are presented in Table 2.

The value of $a_p(\lambda)$ increased as the value of λ decreased. The value of $a_p(\lambda)$ at $z=3$ m in June was larger than at $z=0$ and 6 m, and that at $z=6$ m in August was much larger than at $z=0$ or 3 m. The values of $a_p(\lambda)$ at each depth in September and October were nearly equal.

Absorption by pure water : $a_w(\lambda)$ was obtained by SMITH and BAKER (1981). Values of $a_w(\lambda)$ at 50-nm intervals are also presented in Table 2.

Total absorption by lake water : $a(\lambda)$ is obtained from Eq. (4-1), and vertical distributions of $a(\lambda)$ at 50-nm intervals are presented in Figure 3. Numerals on the lines represent measured months. The values of $a(\lambda)$ at $z=3$ m in June and September were larger than at $z=0$ or 6 m, while that at $z=3$ m in October was smaller than at $z=0$ or 6 m. The value of $a(\lambda)$ at $z=6$ m in August was much larger than at $z=0$ or 3 m. Then the measured values of E_d/E_{d0} at depths deeper than 6 m were shown by open circles in Figure 2, and smaller than the values shown by the straight line. In the same way, vertical distributions of $a(\lambda)$ at $\lambda=570$ and 580 nm were obtained. Figure 4 shows the vertical distributions of $a(\lambda)$ at $\lambda=570$ and 580 nm, and the value of $a(\lambda)$ at $\lambda=570$ or 580 nm became minimum in the region $400\sim 700$ nm.

KISHINO *et al.* (1984) measured $a(\lambda)$ and spectral downward irradiance $E_d(\lambda)$ in Lakes Kizaki and Fukamiike, and Shimoda Nabeta Bay. Let λ_{min} and λ_{max} be wave lengths at which $a(\lambda)$ is minimum and $E_d(\lambda)$ is maximum. The values of λ_{min} and λ_{max} in Lake

Table 2. Values of $a_y(\lambda)$, $a_p(\lambda)$, and $a_w(\lambda)$ at 50-nm intervals.

22 June							
λ (nm)	$z=0$ m			$z=3$ m		$z=6$ m	
	$a_y(\lambda)$ (m^{-1})	$a_p(\lambda)$ (m^{-1})	$a_w(\lambda)$ (m^{-1})	$a_y(\lambda)$ (m^{-1})	$a_p(\lambda)$ (m^{-1})	$a_y(\lambda)$ (m^{-1})	$a_p(\lambda)$ (m^{-1})
400	0.66	0.85	0.02	0.75	1.01	0.93	0.77
450	0.31	0.57	0.02	0.39	0.70	0.53	0.52
500	0.14	0.40	0.03	0.20	0.53	0.34	0.39
550	0.07	0.30	0.06	0.12	0.39	0.24	0.26
600	0.02	0.22	0.24	0.08	0.33	0.18	0.18
650	0.01	0.21	0.35	0.07	0.27	0.13	0.20
700	0	0.16	0.65	0.04	0.29	0.11	0.17
24 August							
400	0.65	0.94		0.77	1.13	0.57	2.28
450	0.25	0.68		0.31	0.86	0.21	1.63
500	0.08	0.50		0.11	0.67	0.07	1.25
550	0	0.38		0.02	0.54	0	0.95
600	0	0.30		0	0.45	0	0.72
650	0	0.24		0	0.40	0	0.66
700	0	0.19		0	0.39	0	0.55
29 September							
400	0.45	1.87		0.58	1.83	0.53	1.82
450	0.18	1.45		0.26	1.44	0.23	1.42
500	0.06	1.19		0.12	1.22	0.10	1.16
550	0.02	0.96		0.07	0.95	0.05	0.94
600	0	0.80		0.04	0.79	0.02	0.76
650	0	0.69		0.03	0.71	0.02	0.69
700	0	0.63		0.02	0.66	0.01	0.60
13 October							
400	0.30	1.71		0.38	1.61	0.52	1.63
450	0.10	1.24		0.15	1.16	0.26	1.19
500	0.01	0.99		0.05	0.93	0.13	0.94
550	0	0.73		0	0.71	0.07	0.73
600	0	0.61		0	0.58	0.04	0.60
650	0	0.53		0	0.51	0.02	0.55
700	0	0.49		0	0.48	0.02	0.51

Kizaki were 570~580 and 570 nm, as were those in Lake Fukamiike. The value of λ_{max} in Nabeta Bay was 488~540 nm, and the value of λ_{min} was nearly equal to the value of λ_{max} . WEIDEMANN and BANNISTER (1986) also measured $a(\lambda)$ and $E_d(\lambda)$ in Irondequoit Bay. The values of λ_{min} and λ_{max} were about 570 and 575~580 nm. Therefore it will be seen that the values of λ_{min} and λ_{max} are nearly equal.

In Lake Oze, the value of λ_{min} was 570 or 580 nm, so the value of λ_{max} may be 570 or 580 nm.

5. Discussion

JERLOV and NYGÅRD (1969) showed that the value of K_d decreases as solar altitude increases because path length of refracted beam to underwater quantum sensor decreases as solar altitude increases. In the measurement in Lake Burley Griffin on 19 November 1975, KIRK (1977) obtained the values of K_d as 2.83 m^{-1} at $h=33^\circ$ and 2.51 m^{-1} at $h=76^\circ$. As in Table 1, the relation between K_d and h was also

Fig. 3. Vertical distributions of $a(\lambda)$ at 50-nm intervals. Fig. 4. Vertical distributions of $a(\lambda)$ at $\lambda = 570$ and 580 nm.

applied in Lake Oze.

When incident direct solar radiation is refracted at lake surface and proceeds into lake water, since the refractive index of water relative to air is 1.333, the angle of incidence i and the angle of refraction j are given by

$$i = 90 - h \quad (5-1)$$

and

$$j = \sin^{-1} \left(\frac{\sin i}{1.333} \right) \quad (5-2)$$

Values of i and j at measured date and time are presented in Table 3.

Let E_0 , E_1 , and E_2 be incident direct solar irradiances on perpendicular planes to the beam at $z=0$, z_1 , and z_2 , and let a be absorption coefficient of lake water. If incident direct solar irradiance is mainly attenuated by absorption of lake water and a at each depth is constant, E_1 and E_2 are given by

$$E_1 = E_0 e^{-az_1 \sec j} \quad (5-3)$$

and

$$E_2 = E_0 e^{-az_2 \sec j} \quad (5-4)$$

Let E_{d1} and E_{d2} be values of E_d at $z=z_1$ and z_2 . E_{d1} and E_{d2} are given by

$$E_{d1} = E_0 \cos j e^{-az_1 \sec j} \quad (5-5)$$

and

$$E_{d2} = E_0 \cos j e^{-az_2 \sec j} \quad (5-6)$$

Therefore E_{d1}/E_{d2} becomes

$$\frac{E_{d1}}{E_{d2}} = e^{a(z_2 - z_1) \sec j} \quad (5-7)$$

When $z_2 - z_1$ is substituted for dz in Eq. (2-1), Eq. (2-1) becomes

$$K_d = \frac{\ln (E_{d1}/E_{d2})}{z_2 - z_1} \quad (5-8)$$

Then, using Eq. (5-7), Eq. (5-8) becomes

$$K_d = a \sec j \quad (5-9)$$

Since the value of λ_{max} in Lake Oze was estimated as 570 or 580 nm, the incident direct solar radiation at $\lambda=570$ or 580 nm must reach a considerable depth. The author calculated the value of K_d for downward irradiance at $\lambda=570$ or 580 nm, and compared with that obtained from Figure 2.

Let $a(570)$ and $a(580)$ be values of $a(\lambda)$ at $\lambda=570$ and 580 nm, and let $a(570)_m$ and $a(580)_m$ be mean values of $a(570)$ and $a(580)$ at $z=0$, 3, and 6 m, except that at $z=6$ m, which was much larger than at $z=0$ and 3 m in August. In Lake Oze, the value of $a(570)_m$ was equal to $a(580)_m$ and is presented in Table 3. When values of j and $a(570)_m$ are given, K_d for downward irradiance at $\lambda=570$ nm is calculated from Eq. (5-9) and presented in Table 3. As in Tables 1 and 3, the calculated values of K_d were in approximate agreement with those obtained from Figure 2 except that in September.

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摘 要

尾瀬沼内の下向きの太陽放射量の垂直減衰係数

1987年の6月から10月まで、7月を除き月一回、尾瀬沼において400～700 nmの範囲の下向きの太陽放射量 E_d を測定した。測定は深度0, 0.1, 0.3, 0.5, 1 m, 1 m以深は1 m間隔で8 mまで行なっ

Table 3. Values of i , j , $a(570)_m$, and K_d .

Date (1987)	Time	i ($^\circ$)	j ($^\circ$)	$a(570)_m$ (m^{-1})	K_d (m^{-1})
22 June	14 : 50	42.1	30.2	0.47	0.54
24 August	15 : 00	50.8	35.5	0.50	0.61
29 September	8 : 40	58.8	39.9	0.98	1.28
13 October	9 : 22	53.2	36.9	0.76	0.95

た。深度 0 m の値は水面直下の値である。

深度 0 m の下向きの太陽放射量を E_{d0} とし、 E_d/E_{d0} の値を対数目盛で表わすと、 E_d/E_{d0} と深度との関係は Figure 2 のごとくほぼ直線で表わされた。Figure 2 から垂直減衰係数を求めると、その値は $0.49 \sim 0.85 \text{ m}^{-1}$ の範囲内であった。

尾瀬沼の湖水の吸収係数は、波長が 570 または 580 nm において最小であった。したがって下向きの太陽放射量は波長 570 または 580 nm において最大と考えられる。

湖水内に入射した太陽放射の減衰が、主に湖水の吸収によるものと考えるならば、波長 570 nm の下向きの太陽放射量の垂直減衰係数は、太陽高度と波長 570 nm の湖水の吸収係数から計算することができる。計算された垂直減衰係数は、9 月を除くと Figure 2 から求められた値とほぼ等しくなることがわかった。

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