Absorption Coefficient of Particulate Matter in Lake Haruna

Akira SUGAWA and Kumiko YAJIMA

Abstract

The absorption coefficient of particulate matter at wave length λ , $a_p(\lambda)$, is expressed by the sum of the absorption coefficients of detritus $a_d(\lambda)$ and phytoplankton $a_{pl}(\lambda)$, and $a_{ph}(\lambda)$ is given by the product of the specific absorption coefficient of chlorophyll-*a* $a_{ph}(\lambda)$ and chlorophyll-*a* concentration at depth z , $C(z)$.

The value of $a_{ph}(\lambda)$ in the region 400~700 nm is maximum at $\lambda=440$ nm, so in Lake Haruna $a_p(440)$ and $C(z)$ were measured, and $a_d(440)$ and $a_{pl}(440)$ were obtained. The value of $a_p(440)$ at $z=12$ m except that on 16 November was much larger than at $z=0, 4$, and 8 m. This may be caused by turbulence which may be effected by bottom current.

When the lake water is divided into some layers, let $a_p(440)_i$ and Δz_i be the value of $a_p(440)$ and thickness of the i -th layer and let z_n be the depth of the lower plane of the n -th layer. For the same solar altitude, absorptance by particulate matter in the lake water between $z=0$ and z_n , $A_p(440)_{zn}$, increases as the value of $\sum_{i=1}^n a_p(440)_i \Delta z_i$ increases. Accordingly, the value of $\sum_{i=1}^n a_p(440)_i \Delta z_i$ in each month was calculated and compared instead of the value of $A_p(440)_{zn}$. Similarly, values of $\sum_{i=1}^n a_d(440)_i \Delta z_i$ and $\sum_{i=1}^n a_{pl}(440)_i \Delta z_i$ were calculated and compared. $a_d(440)_i$ and $a_{pl}(440)_i$ are the values of $a_d(440)$ and $a_{pl}(440)$ of the i -th layer.

Key words : chlorophyll-*a* concentration, specific absorption coefficient of chlorophyll-*a*, bottom current, water temperature.

1. Introduction

The absorption coefficient of particulate matter in sea water was measured by LORENZEN (1972), JERLOV (1976), MOREL and PRIEUR (1977), PRIEUR and SATHYENDRANATH (1981), and MASKE and HAARDT (1987). That in lake water was measured by KIRK (1980), WEIDEMANN and BANNISTER (1986), and SUGAWA (1989), while those in sea and lake waters were measured by KISHINO *et al.* (1984).

When the absorption coefficient of particulate matter and the chlorophyll-*a* concentration are measured, absorption coefficients of detritus and phytoplankton are obtained. PRIEUR and SATHYENDRANATH (1981), and SATHYENDRANATH *et al.* (1987) showed that the specific absorption coefficient of chlorophyll-*a*

in the region 400~700 nm is maximum at 440 nm, so absorption coefficients of particulate matter, detritus, and phytoplankton at 440 nm in Lake Haruna were obtained.

2. Specific absorption coefficient of chlorophyll-*a*

Absorption coefficient of particulate matter at wave length λ , $a_p(\lambda)$, is given by

$$a_p(\lambda) = a_d(\lambda) + a_{pl}(\lambda) \quad (2-1)$$

$$a_{pl}(\lambda) = a_{ph}(\lambda) C(z) \quad (2-2)$$

where $a_d(\lambda)$ and $a_{pl}(\lambda)$ are absorption coefficients of detritus and phytoplankton, respectively, and $a_{ph}(\lambda)$ and $C(z)$ are the specific absorption coefficient of chlorophyll-*a* and chlorophyll-*a* concentration at depth z , respectively. Eq.(2-1) becomes

Fig. 1. Relation between $a_p(440)$ and $C(z)$ on 7 July.

Fig. 2. Vertical distribution of water temperature in Lake Haruna in 1987.

Fig. 3. Relation between $a_p(440)$ and $C(z)$ on 16 November.

$$a_p(\lambda) = a_d(\lambda) + a_{ph}(\lambda) C(z) \quad (2-3)$$

Then $a_p(440)$ and $a_{pl}(440)$ become

$$a_p(440) = a_d(440) + a_{ph}(440) C(z) \quad (2-4)$$

$$a_{pl}(440) = a_{ph}(440) C(z) \quad (2-5)$$

If $a_d(440)$ is constant, the relation between $a_p(440)$ and $C(z)$ is linear.

In Lake Haruna water samples were collected from $z=0, 4, 8, 12$ m, and $a_p(440)$ and $C(z)$ were measured by the methods described by SUGAWA (1989) and SAIJO (1975). The dates of collection are presented in Table 1. The depth of the lake bottom varied from 14.3 to 15.0 m during the period from July to November. Figure 1 shows the relation between $a_p(440)$ and $C(z)$ on 7 July, and the numerals on the open circles present the depths of collection. The open circles are not on a straight line. This indicates that the value of $a_d(440)$ at each depth is not constant. In Lake Haruna water temperature was measured when the water samples were collected. The vertical distribution of the water temperature is shown in Figure 2. In the case on 7 July, the thermocline was clearly recognized as shown in Figure 2. Then the lake water may not be apt to circulate, and detritus concentration at each depth may not become constant.

Figure 3 shows the relation between $a_p(440)$ and $C(z)$ on 16 November, and the numerals on the open circles indicate the depths of collection. The open circles are approximately on a straight line, showing the constant value of $a_d(440)$ at each depth. In this case, from (2-4) the value of $a_p(440)$ at $C(z)=0$ is equal to the value of $a_d(440)$ and the value is 1.52 m^{-1} . In the case on 16 November, the water temperature from $z=0$ to 12 m was constant. Then the lake water may be apt to circulate, and detritus concentration at each depth may become constant.

From the slope of the straight line in Figure 3, the value of $a_{ph}(440)$ is obtained as $0.021 \text{ m}^{-1} (\text{mg Chl-a} \cdot \text{m}^{-3})^{-1}$. LORENZEN (1972), MOREL and PRIEUR (1977) obtained the average value of $a_{ph}(\lambda)$ in the region 400~700 nm as 0.0138 and

$0.0142 \text{ m}^{-1} (\text{mg Chl-}a \cdot \text{m}^{-3})^{-1}$. BANNISTER (1974) proposed the average value as $0.016 \text{ m}^{-1} (\text{mg Chl-}a \cdot \text{m}^{-3})^{-1}$. The value of $a_{ph}(440)$ in Lake Haruna is larger than the above average values.

3. Absorption coefficients of particulate matter, detritus, and phytoplankton

When the values of $a_p(440)$ and $C(z)$ are measured, the value of $a_{pl}(440)$ is obtained from Eq.(2-5), in which the value of $a_{ph}(440)$ is $0.021 \text{ m}^{-1} (\text{mg Chl-}a \cdot \text{m}^{-3})^{-1}$, and the value of $a_d(440)$ is obtained from Eq.(2-4). The values of $C(z)$, $a_p(440)$, $a_d(440)$, and $a_{pl}(440)$ in Lake Haruna are given in Table 1.

The value of $C(z)$ at $z=12 \text{ m}$ except that on 16 November ranged from 20.5 to $107.7 \text{ mg} \cdot \text{m}^{-3}$ and was much larger than at $z=0, 4, 8 \text{ m}$, but that at $z=8 \text{ m}$ on 7 July was $41.0 \text{ mg} \cdot \text{m}^{-3}$ and larger than at $z=12 \text{ m}$. The value of $C(z)$ at $z=8 \text{ m}$ except that on 16 November ranged from 3.7 to $41.0 \text{ mg} \cdot \text{m}^{-3}$ and was larger than at $z=0$ and 4 m . That at $z=12 \text{ m}$ on 16 November was $4.7 \text{ mg} \cdot \text{m}^{-3}$ and slightly smaller than at $z=0, 4, 8 \text{ m}$.

The value of $a_{pl}(440)$ is proportional to the value of $C(z)$, so the vertical distribution of $a_{pl}(440)$ is similar to that of $C(z)$. The value of $a_{pl}(440)$ at $z=12 \text{ m}$ except that on 16 November ranged from 0.43 to 2.26 m^{-1} and was also much larger than at $z=0, 4, 8 \text{ m}$, but that at $z=8 \text{ m}$ on 7 July was 0.86 m^{-1} and larger than at $z=12 \text{ m}$. The value of $a_{pl}(440)$ at $z=8 \text{ m}$ except for 16 November ranged from 0.08 to 0.86 m^{-1} and was larger than at $z=0$ and 4 m . That at $z=12 \text{ m}$ on 16 November was 0.10 m^{-1} and slightly smaller than at $z=0, 4, 8 \text{ m}$.

The value of $a_d(440)$ at $z=12 \text{ m}$ except for 16 November ranged from 1.51 to 7.52 m^{-1} and was much larger than at $z=0, 4, 8 \text{ m}$, and that at $z=8 \text{ m}$ ranged from 0.25 to 0.97 m^{-1} and was larger than at $z=0$ and 4 m . The values of $a_d(440)$ at $z=0$ and 4 m except those on 7 July and 16 November ranged from 0.42 to 0.69 m^{-1} , but those at $z=0$ and 4 m in each month were nearly equal. The value of $a_d(440)$ at each depth on 16 November ranged from 1.50 to 1.54 m^{-1} , and was slightly different from $a_d(440) = 1.52 \text{ m}^{-1}$ obtained in Figure 3. This is caused

Table 1. Values of $C(z)$, $a_p(440)$, $a_d(440)$, $a_{pl}(440)$, and $a_d(440)/a_{pl}(440)$.

Date (1987)	Depth (m)	$C(z)$ ($\text{mg} \cdot \text{m}^{-3}$)	$a_p(440)$ (m^{-1})	$a_d(440)$ (m^{-1})	$a_{pl}(440)$ (m^{-1})	$a_d(440)/a_{pl}(440)$
7 July	0	5.6	0.32	0.20	0.12	1.67
	4	5.2	0.15	0.04	0.11	0.36
	8	41.0	1.11	0.25	0.86	0.29
	12	20.5	7.95	7.52	0.43	17.5
20 August	0	3.7	0.77	0.69	0.08	8.63
	4	6.0	0.77	0.64	0.13	4.92
	8	9.1	1.16	0.97	0.19	5.11
	12	107.7	3.77	1.51	2.26	0.67
24 September	0	5.7	0.54	0.42	0.12	3.50
	4	6.7	0.57	0.43	0.14	3.07
	8	10.5	1.03	0.81	0.22	3.68
	12	94.9	4.29	2.30	1.99	1.16
6 October	0	2.4	0.68	0.63	0.05	12.6
	4	2.1	0.64	0.60	0.04	15.0
	8	3.7	0.94	0.86	0.08	10.8
	12	63.5	4.01	2.68	1.33	2.02
16 November	0	7.0	1.65	1.50	0.15	10.0
	4	5.7	1.65	1.53	0.12	12.8
	8	4.9	1.62	1.52	0.10	15.2
	12	4.7	1.64	1.54	0.10	15.4

Fig. 4. Vertical distribution of $a_p(440)$.

by deviation of the open circles from the straight line in Figure 3, but the mean value becomes 1.52 m^{-1} .

When the value of $a_d(440)$ or $a_{pl}(440)$ is large, from Eq.(2-1) the value of $a_p(440)$ becomes large. The value of $a_p(440)$ at $z=12$ m except for 16 November ranged from 3.77 to 7.95 m^{-1} and was much larger than at $z=0, 4, 8$ m, while that at $z=8$ m ranged from 0.94 to 1.16 m^{-1} and was larger than at $z=0$ and 4 m. The values of $a_p(440)$ at $z=0$ and 4 m except those on 7 July and 16 November ranged from 0.54 to 0.77 m^{-1} , but those at $z=0$ and 4 m in each month were nearly equal. That at each depth on 16 November ranged from 1.62 to 1.65 m^{-1} .

4. Discussion

JERLOV (1976) found a bottom scattering layer

Fig. 5. Vertical distribution of $a_d(440)$.

in which the scattering coefficient was very large, and estimated that the turbulence effected by bottom current leads to an increase of scattering. When part of the sedimented particulate matter is elevated by the turbulence and the particulate matter concentration increases, the value of $a_p(440)$ near the lake bottom may become large.

In Lake Haruna, during the period from July to October, the thermocline was clearly recognized as shown in Figure 2, so the lake water may not be apt to circulate and the particulate matter near the lake bottom may not ascend to the shallow depth. Then the value of $a_p(440)$ at $z=12$ m became much larger than at $z=0, 4$, and 8 m. Since the water temperature between $z=0$ and 4 m was nearly constant, the lake water between $z=0$ and 4 m may be apt to

Fig. 6. Vertical distribution of $a_{pl}(440)$.

circulate, and the values of $a_p(440)$ at $z=0$ and 4 m became nearly equal except for 7 July. On 16 November, a weak thermocline was recognized near the lake bottom and the water temperature from $z=0$ to 12 m was constant, so the lake water may be apt to circulate and the particulate matter near the lake bottom may ascend to the lake surface. Then the value of $a_p(440)$ at each depth became approximately equal.

The value of $a_d(440)$ was usually larger than the value of $a_{pl}(440)$ at the same depth. The ratio of $a_d(440)$ to $a_{pl}(440)$ is given in Table 1 and is often larger than 10. Then the absorption by the particulate matter depends on the detritus.

If a water layer is homogeneous, absorptance by particulate matter at $\lambda = 440$ nm, $A_p(440)$, is

given by

$$\ln \{1 - A_p(440)\} = -a_p(440) \Delta z \sec j \quad (4-1)$$

$$A_p(440) = F_p(440) / F_o(440) \quad (4-2)$$

where j is the angle of refraction of direct solar radiation at $\lambda = 440$ nm at the lake surface, Δz is the thickness of the layer, $F_p(440)$ is radiant flux at $\lambda = 440$ nm lost by the absorption of particulate matter, and $F_o(440)$ is incident radiant flux at $\lambda = 440$ nm into the layer.

If the lake water from $z=0$ to 14 m is divided into the layers $z=0$ to 2 m, 2 to 6 m, 6 to 10 m, and 10 to 14 m, and the values of $a_p(440)$, $a_d(440)$, $a_{pl}(440)$ of the layers are assumed to be equal to those at $z=0, 4, 8$, and 12 m, the vertical distributions of $a_p(440)$, $a_d(440)$, and $a_{pl}(440)$ are shown as in Figures 4, 5, and 6. Let Δz_i be the thickness of the i -th layer and let $a_p(440)_i$, $a_d(440)_i$, $a_{pl}(440)_i$ be the values of $a_p(440)$, $a_d(440)$, $a_{pl}(440)$ of the i -th layer. Let z_n be the depth of the lower plane of the n -th layer and let $A_p(440)_{zn}$, $A_d(440)_{zn}$, and $A_{pl}(440)_{zn}$ be the absorptances by particulate matter, detritus, and phytoplankton in the lake water between $z=0$ and z_n . From Eq.(4-1) $A_p(440)_{zn}$ is given by

$$\ln \{1 - A_p(440)_{zn}\} = - \sum_{i=1}^n a_p(440)_i \Delta z_i \sec j \quad (4-3)$$

similarly, $A_d(440)_{zn}$ and $A_{pl}(440)_{zn}$ are given by

$$\ln \{1 - A_d(440)_{zn}\} = - \sum_{i=1}^n a_d(440)_i \Delta z_i \sec j \quad (4-4)$$

$$\ln \{1 - A_{pl}(440)_{zn}\} = - \sum_{i=1}^n a_{pl}(440)_i \Delta z_i \sec j \quad (4-5)$$

For the same angle of j , from Eq.(4-3) the value of $A_p(440)_{zn}$ increases as the value of $\sum_{i=1}^n a_p(440)_i \Delta z_i$ increases. Similarly, from Eqs. (4-4) and (4-5) the values of $A_d(440)_{zn}$ and $A_{pl}(440)_{zn}$ increase as the values of $\sum_{i=1}^n a_d(440)_i \Delta z_i$ and $\sum_{i=1}^n a_{pl}(440)_i \Delta z_i$ increase. From Figures 4, 5, and 6, the values of $\sum_{i=1}^n a_p(440)_i \Delta z_i$, $\sum_{i=1}^n a_d(440)_i \Delta z_i$, and $\sum_{i=1}^n a_{pl}(440)_i \Delta z_i$ are calculated and given in Table 2. These values were compared instead of the values of $A_p(440)_{zn}$, $A_d(440)_{zn}$, and $A_{pl}(440)_{zn}$.

The values of $\sum_{i=1}^n a_p(440)_i \Delta z_i$ for $z_n=2, 6$, and

Table 2. Values of $\sum_{i=1}^n a_p(440)_i \Delta z_i$, $\sum_{i=1}^n a_d(440)_i \Delta z_i$, and $\sum_{i=1}^n a_{pl}(440)_i \Delta z_i$.

Date (1987)	z_n (m)	$\sum_{i=1}^n a_p(440)_i \Delta z_i$	$\sum_{i=1}^n a_d(440)_i \Delta z_i$	$\sum_{i=1}^n a_{pl}(440)_i \Delta z_i$
7 July	2	0.64	0.40	0.24
	6	1.24	0.56	0.68
	10	5.68	1.56	4.12
	14	37.5	31.6	5.84
20 August	2	1.54	1.38	0.16
	6	4.62	3.94	0.68
	10	9.26	7.82	1.44
	14	24.3	13.9	10.5
24 September	2	1.08	0.82	0.24
	6	3.36	2.56	0.80
	10	7.48	5.80	1.68
	14	24.6	15.0	9.64
6 October	2	1.36	1.26	0.10
	6	3.92	3.66	0.26
	10	7.68	7.10	0.58
	14	23.7	17.8	5.90
16 November	2	3.30	3.00	0.30
	6	9.90	9.12	0.78
	10	16.4	15.2	1.18
	14	22.9	21.4	1.58

10 m on 16 November were 3.30, 9.90, 16.4 and larger than in other months, while that for $z_n = 14$ m was 22.9 and smaller than in other months, because the value of $a_p(440)$ between $z=10$ and 14 m was smaller than in other months. The values of $\sum_{i=1}^n a_p(440)_i \Delta z_i$ for $z_n=2, 6$, and 10 m on 7 July were 0.64, 1.24, 5.68 and smaller than in other months, while that at $z_n=14$ m was 37.5 and larger than in other months, because the value of $a_p(440)$ between $z=10$ and 14 m was much larger than in other months.

The values of $\sum_{i=1}^n a_d(440)_i \Delta z_i$ for $z_n=2, 6$, and 10 m on 16 November were 3.00, 9.12, 15.2 and larger than in other months, but that for $z_n=14$ m was 21.4 and smaller than on 7 July, because the value of $a_d(440)$ between $z=10$ and 14 m was much smaller than on 7 July. The values of $\sum_{i=1}^n a_d(440)_i \Delta z_i$ for $z_n=2, 6$, and 10 m on 7 July were 0.40, 0.56, 1.56 and smaller than in other months, while that at $z_n=14$ m was 31.6 and larger than in other months, because the value of $a_d(440)$ between $z=10$ and 14 m was much larger than in other months.

The value of $\sum_{i=1}^n a_{pl}(440)_i \Delta z_i$ for $z_n=10$ m on 7 July was 4.12 and larger than in other months, because the value of $a_{pl}(440)$ between $z=6$ and 10 m was much larger than in other months. The values of $\sum_{i=1}^n a_{pl}(440)_i \Delta z_i$ for $z_n=2, 6$, and 10 m on 6 October were 0.10, 0.26, 0.58 and smaller than in other months, and that for $z_n=14$ m on 16 November was 1.58 and smaller than in other months. This is due to the small values of $a_{pl}(440)$ between $z=0$ and 10 m on 6 October and between $z=10$ and 14 m on 16 November.

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摘 要

榛名湖内の懸濁物の吸収係数

湖水中の懸濁物の波長 λ の吸収係数 $a_p(\lambda)$ は、植物プランクトン以外の懸濁物の吸収係数 $a_d(\lambda)$ と植物プランクトンの吸収係数 $a_{pl}(\lambda)$ の和で表される。また $a_{pl}(\lambda)$ はクロロフィル- a の単位濃度当りの吸収係数 $a_{ph}(\lambda)$ と深さ z におけるクロロフィル- a の濃度 $C(z)$ の積で表される。 $\lambda=400\sim 700$ nm の範囲では $a_{ph}(\lambda)$ の値は $\lambda=440$ nm で最大となるので、榛名湖において $a_p(440)$ と $C(z)$ の値を測定した。そして $a_d(440)$ と $a_{pl}(440)$ の値を求めた。11 月を除き深さ 12 m での $a_p(440)$ の値は、深さ 0, 4, 8 m での値より大変大きいことがわかった。これは湖底流のため湖底近くで乱流が起り、そのため湖底に沈殿した懸濁物の一部が上昇し、懸濁物の濃度が湖底に近いほど大きくなるためと思われる。

湖水中の懸濁物による absorbance を求めるため、湖面から深さ 14 m までの湖水を 4 層に分けた。第 n 層の下の面の深さを z_n とし、湖面から深さ z_n までの湖水中の懸濁物による $\lambda=440$ nm の absorbance を $A_p(440)_{zn}$ とする。また第 i 層の $a_p(440)$ の値を $a_p(440)_i$ 、その厚さを Δz_i とすると、等しい太陽高度に対して、 $A_p(440)_{zn}$ の値は $\sum_{i=1}^n a_p(440)_i \Delta z_i$ の値が大きいほど大きくなる。従って $A_p(440)_{zn}$ の値の代わりに $\sum_{i=1}^n a_p(440)_i \Delta z_i$ の値を月別に、また z_n を変えて計算し、その値を比較した。同様に $a_d(440)_i$ 、 $a_{pl}(440)_i$ をそれぞれ第 i 層の $a_d(440)$ 、 $a_{pl}(440)$ の値とし、 $\sum_{i=1}^n a_d(440)_i \Delta z_i$ 、 $\sum_{i=1}^n a_{pl}(440)_i \Delta z_i$ の値を計算し、その値を比較した。

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(著者：須川 明，群馬大学教育学部，〒371 前橋市荒牧町4-2；矢島久美子，群馬県衛生公害研究所，〒371 前橋市岩神町3-21-19；Akira SUGAWA, Faculty of Education, Gunma University, Aramaki-cho 4-2, Maebashi 371；Kumiko YAJIMA, Gunma Institute of Public Health, Iwagami-cho 3-21-19, Maebashi 371)

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