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The Relative Importance of Chlorophyll *a*, Non-living Suspended and Dissolved Matter and Water to the Vertical Light Attenuation in the North Basin of Lake Biwa*

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Abstract The relative importance of three components, k_cC, k_cM and K_w to total light attenuation within the euphotic zone was evaluated from the observations in June and September 1982 and the optical characteristics of the respective components in the medium were examined.

The relative importance of the three components to light attenuation in June was substantially different from that in September. A large portion of total light attenuation in June was attributed to non-living suspended and dissolved matter, being about 73% of total light attenuation. On the other hand, contribution of living phytoplankton was high in September in spite of the low PC/seston ratio. The optical property of the water column in June was characterized by the absorption due to non-living suspended and dissolved matter. In September, it was characterized by the scattering, because of low PC/seston ratio.

Introduction

Light intensity which penetrates the surface of the ocean and lake is principally absorbed by the optical components like suspended particles, dissolved matter and water itself. The suspended particles can be further divided into living phytoplankton and non-living particles. The amounts of phytoplankton, non-living suspended particles and dissolved matter differ regionally and seasonally. Hence, it is expected that the relative importance of each component to vertical light attenuation varies from water body to water body, and from season to season. Jerlov (1976) found that regional difference in light attenuation depended on the dissolved organic carbon contents. On the basis of data on chlorophyll and light penetration in various ocean systems, Lorenzen (1972) reported that euphotic depth (defined as the depth to which 1% of the incident radiation penetrates) was determined by the relative importance of these components related to the light attenuation, and, in water body with shallow euphotic zone, light absorption was mostly due to phytoplankton. As pointed out by Walker (1982), however, determination of euphotic zone from data on chlorophyll is

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different for the waters where are influenced by terrestrial input or substantial resuspension of sediments.

As a part of the analysis of light utilization by phytoplankton (Tsuda 1980; Tsuda & Nakanishi 1985; Tsuda & Nakanishi in preparation), light attenuation and concentrations of chlorophyll *a* and suspended particles were measured in the stratified periods in the north basin of Lake Biwa to determine the relative importance of each component to vertical attenuation of light in the euphotic zone and to examine the optical characteristics of the water column.

Materials and Methods

The observations were carried out in June and September 1982 at Stn. P (ca. 42 m depth) in the north basin of Lake Biwa (Fig. 1). The water samples for determinations of chlorphyll *a* (Chl-*a*), seston, and particulate carbon (PC) were collected at intervals of 3 h from the depths of 0, 1, 2.5, 5, 7.5, 10, 15 and 20 m in June and 0, 2.5, 5, 7.5, 10, 15, 20, 30 and 39 m in September. The samples on glass fiber filter (Whatman GF/C) pretreated at 450°C for 4 h were subjected to the determinations of Chl-*a* and PC. Chl-*a* amount was measured by the method of Lorenzen (1967) and PC with a CHN analyzer (YANACO, MT-2). Dry weight of seton in the samples on a Millipore filter (HAWP 0.47, pore size; 0.45 μm) was determined by the gravimetric method.

Light measurements were conducted several times in a day at various depths using a scalar quanta meter (Biospherical Instr., QSP-200; Booth 1976) which detects wavelengths from 370 to 700 nm.

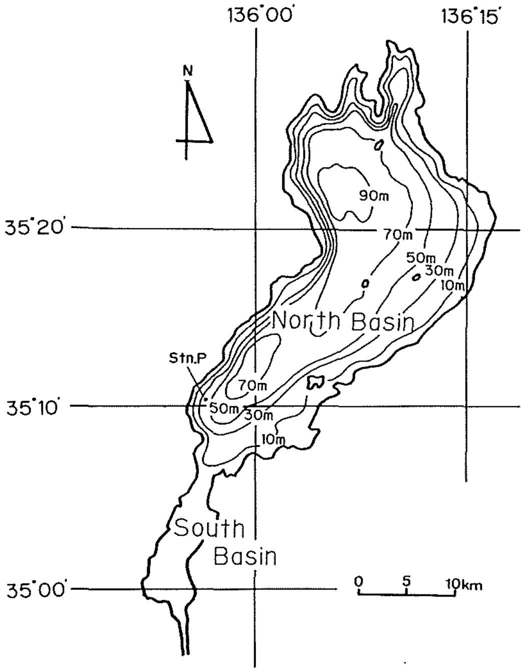

Fig. 1. Location of study site in the north basin of Lake Biwa.

Lorenzen (1972) partitioned light attenuation into three components as follows:

$$K_t Z = K_w Z + k_c C_{1\%} + k_d M_{1\%} \tag{1}$$

where Z is the depth of euphotic zone, K_t the averaged diffuse attenuation coefficient within the euphotic zone, K_w, k_c, and k_d attenuation coefficients for water itself, phytoplankton, and non-chlorophyll and dissolved matter, respectively. The $C_{1\%}$ and $M_{1\%}$ are the integrated chlorophyll concentration and the averaged concentration of non-living suspended and dissolved matter within the euphotic zone.

When we considered attenuation coefficient $K(Z)$ in a layer (1 m thickness) between 0.5 m above and below the sampling depth of Chl-*a*, Lorenzen's equation can be rewritten in a form given by

$$K(Z) = K_w + k_c C + k_d M \tag{2}$$

where $K(Z)$ is the diffuse attenuation coefficient by 1-m layer of water. The C and M are concentrations of Chl-*a*, and non-living suspended and dissolved matter within the layer of 1 m thickness, respectively. In the present study, the K_w value was assumed as $0.034\,\mathrm{m}^{-1}$ (Lorenzen 1972; Walker 1982; MacPherson & Miller 1987). The $k_d M$ in equation (2) can be obtained by subtracting $K_w + k_c C$ from $K(Z)$.

The diffuse attenuation coefficient $K_q(Z)$ of scalar quantum irradiance E_q attenuated in a layer with 1 m thickness is computed as follow:

$$K_q(Z) = \frac{1}{\Delta Z} \ln \frac{E_q\left(Z - \frac{1}{2}\Delta Z\right)}{E_q\left(Z + \frac{1}{2}\Delta Z\right)} \tag{3}$$

where ΔZ is a layer with 1 m thickness. $K_q(Z)$ is assumed to be approximately equal to $K(Z)$. The averaged $\overline{K}$ from the surface to the euphotic depth was obtained from the integration of $K_q(Z)$.

Results

Euphotic depths and their relation to composition of suspended particles

Figure 2 shows the depths of 50, 10, and 1% of the surface scalar quantum irradiance $E_q(0)$ at each measured time in June and September. The 1% depth, namely euphotic depth Z_{eu}, varied from 17 to 18.5 m in June and from 11 to 13.4 m in September. Light attenuation in June was lower than that in September. This tendency was clearly reflected to Chl-*a* and seston contents in the euphotic zone (Table 1). Composition of suspended particles can be roughly estimated by PC/seston ratio as presented by Morel (1982). The PC/seston ratio, averaging 34% in the euphotic zone was significantly higher in June than that (average, 18%) in September. The high ratio in June suggests that suspended particles in the euphotic zone were mainly composed of biogenous origin. But, on the contrary, the Ch-*a*/PC ratio was low in June. Judging from the high PC/seston and the low Chl-*a*/PC ratios, the attenuation of light in June appears to have been closely related to absorption due to non-living organic particles. According to Morel's presentation, the contribution of inorganic suspended particles to

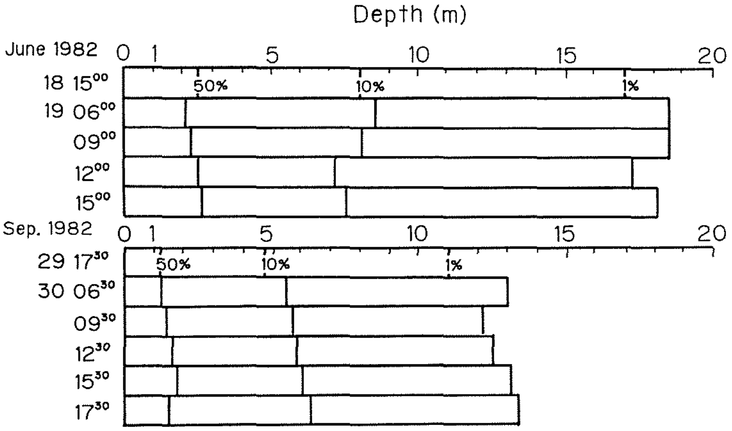

Fig. 2. The depths where $E_q(Z)$ is reduced to 50, 10, and 1% of its value above the surface show at each measured time.

Table 1. Euphotic depth, seston, Chl-*a* and PC contents within the euphotic zone measured in June and September, 1982.

Date	Z(1%) (m)	Chl-*a* (mg·m^{-2})	Seston (g·m^{-2})	PC (g·m^{-2})	PC / Seston (%)	Chl-*a* / PC (%)
1500 18 June	17.0	37.6	17.2	6.2	36.0	0.61
1800	18.5	36.9	17.5	5.9	33.7	0.63
0600 19 June	18.5	37.3	21.1	6.2	29.2	0.60
0900	17.3	32.5	13.0	5.1	39.2	0.64
1200	18.1	35.7	18.7	6.1	32.6	0.59
1730 29 Sep.	11.0	84.8	48.5	8.3	17.1	1.02
0630 30 Sep.	13.0	113.3	58.4	10.2	17.5	1.11
0930	12.2	118.2	55.4	10.0	18.1	1.18
1230	12.5	115.5	53.9	10.3	19.1	1.12
1530	13.1	128.4	57.1	10.9	19.1	1.17
1730	13.4	119.1	53.4	10.3	19.3	1.16

seston appears to have been relatively high in September with the low PC/seston ratio. The relatively high Chl-*a*/PC ratio suggested that share of living phytoplankton in suspended particles of biogenous origin was high in September.

Specific attenuation of chlorophyll

Specific attenuation coeffiicient k_c for chlorophyll can be determined with chlorophyll concentration and diffuse attenuation coefficient computed from scalar quantum irradiance. This value equals to the slope of the regression line of K_q on Chl-*a* (Dubinsky & Berman 1979). Though k_c is an attenuation coefficient being varied by cell size and shape (Kirk 1975a, 1975b), composition of phytoplankton (Atlas & Bannister 1980; Shanz 1985) and physiological state (Dubinsky & Berman 1979), in the present study, a value of k_c was assumed to be constant in the euphotic zone.

In June and September, relationship between chlorophyll *a* concentration C and diffuse attenuation coefficient K_q was expressed as

$$\begin{aligned} \text{June}: \quad & K_q = 0.015C + 0.183 \quad (r^2 = 0.625,\ p = 0.01;\ N = 24) \\ \text{September}: \quad & K_q = 0.022C + 0.157 \quad (r^2 = 0.624,\ p = 0.01;\ N = 24) \end{aligned} \tag{3}$$

The k_c values obtained were 0.015 and 0.022 $\mathrm{m^{-1}/mgChl\text{-}a\ m^{-3}}$ in June and September, respectively, falling in the range given by some researchers (Table 2).

Table 2. The k_c values in some lakes.

Lake	Spectral range	k_c ($\mathrm{m^2 mgChl\text{-}a^{-1}}$)	n	r^2	Reference	
Lake George	red (535–685 nm)	0.016	48	0.95	Ganf**	1974
Lough Neagh	Par (400–700 nm)	0.011	48	0.66	Jewson**	1977
Port Hacking	PAR	0.021	73	0.58	Scott	1978
Lake Minnetonka	PAR	0.022*	9	0.93	Megard, et al.	1979
Lake Kinneret	PAR	0.0067	43	0.66	Dubinsky and Berman	1979
Onondoga Lake	PAR	0.0109	118	0.46	Field and Effler	1983
Castle Lake	PAR	0.016	50	0.40	Priscu	1983
Lake Constance	PAR	0.015*	—	0.81	Tilzer	1983
Lake Biwa June, 1982	PAR	0.015*	24	0.63	Present study	
Sep., 1982	PAR	0.022*	24	0.62	Present study	

* Measurements of scalar quantum irradiance

** Cited from Kirk (1983)

Table 3. The total attenuation coefficients within the euphotic zone and the relative importance of each component.

Date	K ($\mathrm{m^{-1}}$)	K_w	k_cC	K_dM
		K (%)	K (%)	K (%)
1500 18 June 1982	0.280	13.9	11.8	74.3
1800	0.257	15.5	17.3	67.2
0600 19 June	0.279	14.4	11.6	74.0
0900	0.280	14.4	10.8	74.8
1200	0.284	15.4	11.7	72.9
Average	0.276	14.7	12.6	72.7
1730 29 Sep. 1982	0.436	8.1	42.6	49.3
0630 30 Sep.	0.396	10.0	50.8	39.2
0930	0.408	9.5	53.1	37.4
1230	0.392	9.9	52.5	37.6
1530	0.348	11.2	53.2	35.6
1730	0.328	11.9	51.3	36.8
Average	0.385	10.1	50.6	39.3

Compositions of attenuation

Using equation (2), the components of $K(Z)$ were estimated on the basis of data on *in situ* measurements. Total attenuation coefficient K and contribution percentages of the respective components to K within the euphotic zone in June and September were calculated (Table 3). In June, the contribution percentage of non-living suspended and dissolved matter k_dM to total light attenuation was very high and attained to 73%. Chl-*a* was a minor contributor (13%). This fact indicates that a large portion of light attenuation was attributed to absorption of the optical property. In September, non-living suspended and dissolved matter accounted for 39% of total light attenuation, Chl-*a* for 51% and water for the remainning 10%, respectively. Thus, Chl-*a* was the highest contributor to light attenuation. However, averaged PC/seston ratio within the euphotic zone was relatively small, indicating that suspended matter was predominated by inorganic particles. This suggested that the intense scattering influenced also to the light attenuation. This scattering is well competed for light available to phytoplankton photosynthesis (Kirk 1983).

Discussion

We partitioned total light attenuation into three components, Chl-*a*, non-living suspended and dissolved matter, and water itself and examined the relative importance of each component to light attenuation in June and September of 1982 in Lake Biwa.

The relative importance of the above-mentioned three components to light attenuation was different between June and September. The percentage contribution of non--living suspended and dissolved matter to the light attenuation was large and 73% in June, whereas that of Chl-*a* was relatively great in September.

After Lorenzen (1972), if light attenuation is not influenced by land run off, it depends mainly on phytoplankton concentration in the productive waters when the euphotic depth is around 10 m depth, while it comes to be strongly influenced by non-living suspended matter in the waters with euphotic depth of 30–40 m and by water itself in the waters with euphotic depth more than 70 m. Figure 3 shows variations of the percentage contribution of the respective components, k_cC, k_dM and K_w to the average light attenuation coefficient, K within euphotic layer calculated from the oceanic data by Lorenzen (1976) against various euphotic depths and included values determined in June and September. The values of k_cC/K on the euphotic depth in June were separated far from the k_cC curve obtained from the Lorenzen's data. This is due to great contribution of non-living organic suspended matter to light attenuation in the euphotic layer (cf. Table 3). Thus, there is no substantial relation between Chl-*a* concentration and the euphotic depth in June. On the other hand, the k_cC/K values on the euphotic depth in September were close to the k_cC curve. This suggests that Chl-*a* concentration is a main contributor for determination of the euphotic depth.

Variations of the euphotic layer being attended with change in underwater light condition will be linked to photosynthesis of phytoplankton. The euphotic depth was deeper in June as compared with that in September and the averaged light attenuation coefficient within the euphotic layer was lower. This means that only the underwater light condition for phytoplankton photosynthesis in June was better than that in

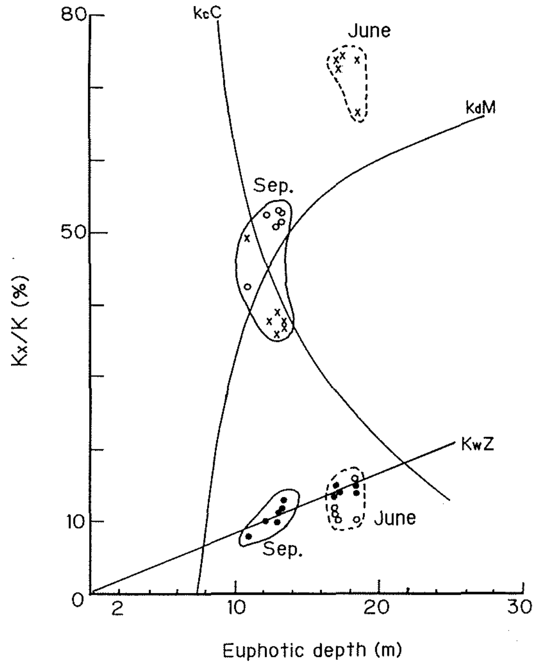

Fig. 3. Percentages of chlorohyll (○), non-living suspended and dissolved matter (×), and water (●) to the toal light attenuation within the euphotic zones. Solid lines represent curves derivered from equation given by Lorenzen (1976).

September. However, it should keep in mind that a large percentage of light attenuation depended on non-living suspended, mainly organic matter and dissolved matter. These components absorb the light intensity strongly in the water. The effective light utilization of phytoplankton depends on the absorption property. Hence, it is considered that phytoplankton may have been less favourable condition from the viewpoint of light utilization than that in September. As a result, primary production is possible to be reduced its efficiency. Total vertical attenuation coefficient was quite high because of the rapid attenuation of light in September and so the euphotic depth was relatively shallow. A major portion of the suspended matter was composed of inorganic substances, which do not absorb the light intensity strongly despite of the intense scattering (Table 1). Taking into consideration this optical property, it is considered that phytoplankton can absorb more efficiently the light avaliable for the photosynthesis despite of rapid attenuation of light within the euphotic layer. This condition for phytoplankton may be one of causes to raise the high productivity in September. In the medium of this type, primary production accounts for high productivity as presented by Oertel and Dunstan (1981).

For study on the primary productivity of phytoplankton, it will be required to analyze the optical characteristics of phytoplankton, non-living suspended matter, dissolved matter and water itself in connection with light attenuation. Further, in the waters with shallow euphotic zone, not only relative contribution of the respective components to the light attenuation but also their optical properties should be examined for full understanding of the light utilization efficiencies by phytoplankton photosynthesis.

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References

Atlas, D. and T. T. Bannister (1980) Dependence of mean spectral extinction coefficient of phytoplankton on depth, water color, and species. *Limnol. Oceanogr.* 25: 157–159.

Booth, C. R. (1976) The design and evaluation of a measurement system for photosynthetically active quantum scalar irradiance. *Limnol. Oceanogr.* 21: 326–336.

Dubinsky, Z. (1980) Light utilization efficiency in natural phytoplankton communities. In *Primary Productivity in the Sea.* Edited by P. G. Falkowski. p. 83–97. Plenum Publishing Corp. New York.

Dubinsky, Z. and T. Berman (1979) Seasonal changes in the spectral composition of downwelling irradiance in Lake Kinneret (Israel). *Limnol. Oceanogr.* 24: 652–663.

Field, S. D. and S. W. Effler (1983) Light attenuation in Onondago Lake, NY, USA, 1978. *Arch. Hydrobiol.* 98: 409–421.

Jerlov, N. G. (1976) *Marine Optics.* p. 55–63. Elsevier Scientific Publishing Co., New York.

Kirk, J. T. O. (1975a) A theoretical analysis of the contribution of algal cells to the attenuation of light within natural waters. I. General treatemt of suspensions of pigmented cells. *New Phytol.* 75: 11–20.

Kirk, J. T. O. (1975b) A theoretical analysis of the contribution of algal cells to the attenuation of light within natural waters. II. Spherical cells. *New Phytol.* 75: 21–36.

Kirk, J. T. O. (1983) *Light Photosynthesis in Aquatic Ecosystems.* p. 260–261. Cambridge Univ. Press, London.

Lorenzen, C. J. (1967) Determination of chlorophyll and phaeopigments; spectrophotometric equations. *Limnol. Oceanogr.* 12: 343–346.

Lorenzen, C. J. (1972) Extinction of light in the ocean by phytoplankton. *Jour. Cons. int. Explor. Mer.* 34: 262–267.

Lorenzen, C. J. (1976) Primary production in the sea. In *The Ecology of the Seas.* Edited by D. H. Cushing and J. J. Walsh. p. 173–185. W. B. Saunders.

Megard, R. O., W. S. Combs, Jr., P. D. Smith, and A. S. Knoll (1979) Attenuation of light and daily integral rates of photosynthesis attained by planktonic algae. *Limnol. Oceanogr.* 24: 1038–1050.

Morel, A. (1982) Optical properties and radiant energy in the waters of the Guinea Dome and the Mauritanian upwelling area in relation to primary production. In *The Canary Current: Stusies of an Upwelling Systems.* Edited by G. Hemrel. p. 94–107. Rapp. R.-v. Reun. Cons. int. Explor. Mer, 180. Copenhague K Danemark.

McPherson, B. F. and R. L. Miller (1987) The vertical attenuation of light in Charlotte Harbor, a shallow, subtropical estuary, south-western Florida. *Estuar., Coast. Shelf Scie.* 25: 721–737.

Oertel, G. F. and W. M. Dunstan (1981) Suspended-sediment distribution and certain aspects of phytoplankton production off Georgia, U.S.A. *Marine Geology.* 40: 171–197.

Priscu, J. C. (1983) Suspended characteristics in subalpine Castle Lake, California. II. Optical properties. *Arch. Hydrobiol.* 97: 425–433.

Scott, B. D. (1978) Phytoplankton distribution and light attenuation in Port Hacking estuary. *Aust. Jour. Mar. Freshwater Res.* 29: 31–44.

Shanz, F. (1985) Vertical light attenuation and phytoplankton development in Lake Zürich. *Limonl. Oceanogr.* 20: 299–310.

Tsuda, R. (1980) Measurements of underwater spectral irradiance in Lake Biwa. *Jpn. Jour. Limmol.* 41: 57–67.

Tsuda, R. and M. Nakanishi (1985) Light utilization efficiencies by phytoplankton in Lake Biwa. *Bull Mar. Scie.* 37: 779.

Tilzer, M. M. (1983) The importance of fractional light absorption by photosynthetic pigments for phytoplankton productivity in Lake Constance. *Limnol. Oceanogr.* 28: 833–846.

Walker, O. S. Jr. (1982) The relative importance of chlorophyll, dissolved and particulate material, and seawater to the vertical extinction of light. *Estuar., Coast. Shelf Scie.* 15: 459–465.

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