Comparative Measurements of Underwater Irradiance in Illuminance, Quanta and Energy in Lake Biwa*

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Abstract

Underwater irradiances were measured in Lake Biwa in terms of lux, quanta (400-700 nm) and total energy in the shortwave range (300-2500 nm). The attenuation of irradiance was most rapid in energy, least in illuminance and in-between in quanta. Similar results were obtained from computations using the spectral sensitivity of sensors in conjunction with the earlier reported measurements of underwater spectral irradiance obtained for Lake Biwa. Thus, the differential attenuation of irradiance among these three expressions is due to the differences in the spectral sensitivity among the sensors together with characteristics of Lake Biwa regarding the selective absorption of spectral irradiance. Computed results also indicated that the penetration of energy flux in the range of 400-700 nm was virtually equal to that of photon flux.

Analysis and discussion are extended to other lakes and marine environments reported in the literature. The significant deviations of underwater irradiance in lux from irradiance as photon flux density underscores the importance of using quanta or energy measurements in the photosynthetically active wavelength range in studies of primary production in aquatic habitats.

1. Introduction

Among environmental factors in aquatic habitats, underwater radiation, together with water temperature, has been given utmost attention since the earlier stages of hydrobiology. The classical approach used photographic films, exposing them to light at depths under water. This approach had been replaced by the use of photocell lux meters since the 1930s. The use of lux (or other photometric units) measurements enjoyed widespread acceptance among biologists, until very recently. But, it is now well-known that the action spectrum of photosynthesis is quite different from the spectral sensitivity of lux meters which matches the characteristics of the average normal human eye. It is the number of quanta of light available in the photosynthetically active wavelength range that is most directly related to the photosynthetic light reactions. Accordingly, Working Group 15 on photosynthetic radiant energy in the ocean (IAPSO, SCOR, 1965) has

recommended that light measurements in photosynthetic studies be made in terms of quanta within the range 350-700 nm. The measurement and expression of irradiance in terms of quanta is now becoming increasingly popular (e.g., BOOTH, 1976; CHAPMAN *et al.*, 1976; JERLOV, 1976; UPHOFF and HAGENVADER, 1976; KIRK, 1977; ROEMER and HOAGLAND, 1979).

Although the use of quantum meters and units is most desirable in studies of primary production, it is a rather recent occurrence (JERLOV and NYGÅRD, 1969) and still limited in practice, primarily due to the difficulties with instrumentation. Instead, another expression or measurement of irradiance, that is, irradiance in terms of energy units, has been more predominant in most physical and biological studies of aquatic ecosystems. Thus, several investigations have been made to assess how differences in expression or measurement of irradiance affect the interpretation of the physical and the biological properties of aquatic environments. JERLOV and NYGÅRD (1969) were the first to study the behavior of the ratio of quanta to energy at depths

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in water by measuring these quantities with the meters newly devised by themselves. MOREL and SMITH (1974) studied theoretically the behavior of this ratio both above and below the surface of waters, on the basis of the quanta and energy estimated from a number of data on spectral irradiance.

Theoretical comparisons of the attenuation of light were also made among energy, quanta and lux (OKAMI *et al.*, 1978). No attempt has been made thus far to measure underwater irradiance in terms of lux, quanta and energy simultaneously. It is therefore interesting to make an experimental comparison of the attenuation of irradiance in the natural waters among these three expressions to see how irradiance measured as quanta (i.e., quantity most closely related to the light reaction of photosynthesis) is related to the other two. This attempt will also make it possible to check the results of theoretical investigations so far reported.

This study reports some results from direct measurements of underwater irradiance in Lake Biwa in terms of lux, quanta (400-700 nm) and total energy in the shortwave range (300-2500 nm). Additionally, attenuation of energy flux in the photosynthetically active range (400-700 nm) is computed using measurements of underwater spectral irradiance in Lake Biwa as reported in TSUDA (1980). Attenuation of irradiance measured or expressed in these four quantities is compared and the differences are discussed on the basis of theoretical analysis. Analysis and discussion are extended to other lakes and marine environments reported in the literature.

2. Site and Methods

Lake Biwa, the largest freshwater lake in Japan, is located in Shiga Prefecture on the main island of Japan. It comprises two lakes of different sizes: the Southern Lake, smaller and shallower; and the Northern Lake, much larger and deeper (Fig. 1). Measurements were made at three locations on board: Station A, located at the south-

ernmost end of the Northern Lake with a depth of some 9 m; Station B, located around the center of the Southern Lake with a depth of some 4 m; and Station C about 200 m from the Otsu Hydrobiological Station, Kyoto University (35°03' N, 135° 53' E), with a depth of some 2 m. Table 1 gives the date and time of measurements, weather conditions during the measurements, and quantities measured.

Irradiances in terms of photon flux density ($\mu\text{E}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) and of illuminant flux density (lux) were measured with a multi-function irradiance meter (LI-COR Ltd., Lincoln, Nebraska, USA). The instrument uses multi-function millivolt meter (Model LI-185A) in conjunction with a photometric sensor to measure illumination or a quantum sensor to measure photons in the 400-700 nm waveband. We used two LI-185A meters; one with a photometric sensor (Model LI-210S) or a quantum sensor (Model LI-190S) to measure surface irradiance, and another with an underwater photometric sensor (Model LI-212S) or an underwater quantum sensor (Model LI-192S) to measure underwater irradiance at various depths. To measure underwater irradiance as energy, we used a waterproof thermopile pyranometer (Model MS-800, Ekoseiki Ltd., Japan). Readings of LI-190S quantum sensor in the atmosphere also served for rapid comparison with the submerged pyranometer, after being converted to energy flux density using a predetermined relationship between quantum and energy *in situ*. All the three underwater sensors were attached to a mounting and leveling fixture. Measurements in the air and water were obtained simultaneously, and underwater readings at various depths were expressed relative to the subsurface readings. Figure 2 provides spectral sensitivity for the quantum and the photometric sensors and for the thermopile pyranometer.

3. Results and Discussion

3-1. Lake Biwa

Underwater irradiances measured at three

Fig. 1. Map of Lake Biwa showing the locations of measurements. Station A is located at the southernmost end of Northern Lake, and Station B around the center of Southern Lake. Another set of on-board measurements was made at Station C, about 200 m off the Otsu Hydrobiological Station.

Table 1. Date, time and weather conditions of on-board measurements of underwater irradiance at three locations in Lake Biwa.

Date	Quantities measured	A*		Station B*		C**	
		Time	Weather	Time	Weather	Time	Weather
Dec. 7, 1979	Illuminance and quanta	1210-1240	Clear	1320-1340	Overcast		
Nov. 4, 1980	Illuminance, quanta, and energy					1130-1230	Clear
Nov. 25, 1980	Illuminance, quanta, and energy	1215-1240	Clear	1420-1510	Fine with occasional clouds		

* See Fig. 1 for the locations of Stations A and B.

** Station is about 200 m off the Otsu Hydrobiological Station (Fig. 1).

Fig. 2. The spectral sensitivity for (a) the photometric sensor, (b) the quantum sensor, and (c) the thermopile pyranometer. Data provided by the manufacturers: (a) and (b) by LI-COR Ltd., and (c) by EKO-SEIKI Ltd.

Table 2. Vertical distribution of spectral irradiance in Lake Biwa. Values are obtained from Fig. 3 in TSUDA (1980) where measurements were made at the northernmost end of the Southern Lake in October 1975 and in December 1976. Unit: $\mu\text{W}\cdot\text{cm}^{-2}\cdot\text{nm}^{-1}$.

Expedition	Depth (m)	Wavelength (nm)						
		433	466	505	528	562	604	665
I Oct. 1975	0*	8.8	7.2	7.2	7.0	7.0	5.7	4.3
	1	3.5	4.1	4.8	5.0	5.0	3.4	2.0
	2	1.5	2.3	3.0	3.1	3.1	2.0	0.7
	3	0.6	1.4	2.0	2.1	2.0	1.1	0.3
	5	0.1	0.4	0.7	1.0	1.0	0.5	0.1
II Dec. 1976	0*	28.0	28.0	24.0	21.5	18.0	18.5	15.5
	1	8.0	10.0	12.0	12.0	12.0	10.0	7.0
	3	0.8	1.8	3.0	3.7	4.0	2.5	0.5
	5	0.1	0.2	0.4	0.7	1.0	0.5	0.1
	6	0.0	0.1	0.3	0.4	0.6	0.3	0.0

* This depth denotes the layer immediately below the surface. The spectral irradiance at this depth was estimated by extrapolation of values measured at and below 1 m depth.

Fig. 3. Change with depth in the relative underwater irradiance as measured in units of lux ($\circ$), quanta ($\bullet$) or energy ($\times$). See Fig. 1 for locations.
 (a): Measurements at Station A (top) and at Station B (bottom) on December 7, 1979.
 (b): Measurements at Station C on November 4, 1980.
 (c): Measurements at Station A (top) and at Station B (bottom) on November 25, 1980.

locations either as illuminance, quanta or energy all declined exponentially (Fig. 3). The attenuation of irradiance was most rapid in energy, least in illuminance and in-between in quanta. It is obvious that such differences are likely due to the differences in the spectral sensitivity of the sensors and changes in the spectral composition of radiation with depth in water. To examine this inference quantitatively, we computed irradiance at depths in units of energy flux density (E_{TW}), photon flux density (E_Q), and illuminant flux density (E_I), using the spectral sensitivity of the sensors (Fig. 2) in conjunction with the measurements of underwater spectral irradiance obtained for Lake Biwa (TSUDA, 1980).

The procedures for computation were basically the same as those of SMITH *et al.* (1973):

(i) Spectral irradiances for seven wavelengths at five depths in water (Table 2), derived from TSUDA (1980, Fig. 3), were expressed relative to the subsurface values (Table 3).

(ii) Relative underwater irradiances (RUI) thus computed were plotted against depth (D , m) on a semi-log scale and fitted to the equation

$$RUI = \exp(-k_\lambda D) \quad (1)$$

to compute the attenuation coefficient (k_λ , m^{-1}). Results are also given in Table 3.

(iii) The attenuation coefficient was plotted against the wavelength and the eye-fitted relation between these two variables was established (Fig. 4). From these fitted curves, the average attenuation coefficient ($\bar{k}_i$, m^{-1}) was calculated for each waveband as in Table 4.

(iv) Total irradiance in successive wavebands ($\hat{E}_i$, $W \cdot m^{-2}$) was computed for the same nine bands as (iii), from the spectral distribution of global radiation (300–2500 nm) given as Fig. 74 in JERLOV (1976). Results are also listed in Table 4.

(v) By definition, RUI measured with

Table 3. Spectral irradiance at depths expressed relative to the subsurface value and the computed spectral attenuation coefficient $k_\lambda(\text{m}^{-1})$. The relative values were derived from Table 2. k_λ is the average over the layer of 5 m depth (I) or of 6 m depth (II).

Expedition	Depth (m)	Wavelength (nm)						
		433	466	505	528	562	604	665
I Oct. 1975	0*	100	100	100	100	100	100	100
	1	39.8	56.9	66.7	69.4	71.4	60.0	46.5
	2	17.1	31.9	41.7	43.1	44.3	35.1	15.4
	3	7.2	19.4	27.8	29.2	28.6	19.3	7.2
	5	1.1	5.6	9.7	14.3	14.3	8.8	1.6
	k	0.89	0.58	0.46	0.40	0.40	0.50	0.85
II Dec. 1976	0*	100	100	100	100	100	100	100
	1	28.6	35.7	50.0	55.8	66.7	54.0	45.2
	3	2.9	6.4	12.5	17.2	22.2	13.5	2.5
	5	0.2	0.6	1.8	3.3	5.6	2.7	0.5
	6	0.0	0.3	1.0	1.9	3.3	1.6	0.1
	k	1.25	1.00	0.77	0.64	0.56	0.70	1.15

* This depth denotes the layer immediately below the surface (subsurface).

Fig. 4. Attenuation coefficient (k_λ) as a function of wavelength. Eye-fitted curves, I and II, were obtained for the corresponding two sets of data given in Table 3.

a sensor which has the spectral sensitivity S_i can be calculated from the equation

$$\text{RUI} = \frac{\sum_{i=1}^n S_i \hat{E}_i \exp(-k_i D)}{\sum_{i=1}^n S_i \hat{E}_i} \quad (2)$$

where i denotes the successive waveband as given in Table 4 and n the number

of the wavelength blocks under consideration.

Results from the above calculations (I and II in Table 5) show that, at any water depth, $\text{RUI} > \text{RE}_q > \text{RE}_{\text{TW}}$. This corresponds to the measured results (in Table 5 or in Fig. 3-c, top), although the calculated RUI, especially RE_{TW} , exceeded the measured one at all depths. We can therefore conclude that, in Lake Biwa, the attenuation of irradiance is most rapid in energy of 300-2500 nm spectral band, least in illuminance and in-between in quanta, as a result of the differences in the spectral sensitivity among the sensors and lakewater characteristics as regards the selective absorption of spectral irradiance. In other words, RE_i is the greatest because the green light that is most highly sensed with the photometric sensors remains least attenuated in this lake, whereas $\hat{E}_i$ above the surface varies only slightly with the waveband in the range of the visible region (400-700 nm). Likewise, RE_{TW} is the least among the three quantities because the pyranometers sense irradiance non-selectively within the range of 300 to 2500 nm, while the long-

Table 4. Attenuation coefficient $\bar{k}_i$ (m^{-1}) and energy content above the lake surface $\hat{E}_i$ ($W \cdot m^{-2}$) for the i -th spectral band. $\bar{k}_i$ was estimated from Fig. 4 as the average over each wavelength block. $\hat{E}_i$ was computed from the spectral irradiance data obtained above the sea surface by JERLOV (1976).

Spectral region (nm)	Number of spectral band (i)								
	1	2	3	4	5	6	7	8	9
	300- 400	400- 450	450- 500	500- 550	550- 600	600- 650	650- 700	700- 800	800- 2500
$\bar{k}_i$ (I*)	1.84	0.97	0.57	0.41	0.40	0.60	0.94	1.62	10.54
$\bar{k}_i$ (II*)	2.23	1.31	0.95	0.65	0.58	0.84	1.23	1.95	10.67
$\hat{E}_i$ ($W \cdot m^{-2}$)	55	63	80	74	70	68	63	100	340

* See Table 2 for the symbols of I and II.

Table 5. Comparisons between computed and measured relative underwater irradiances in terms of energy in the total shortwave range (RE_{TW}), energy (RE_{PW}) and quanta (RE_Q) in the photosynthetically active range, and lux (RE_I). Computed I and II were obtained with eq. (2) in which $\bar{k}_i$ (I) and $\bar{k}_i$ (II) in Table 2 were used respectively. Measured values are those obtained at Station A (see Fig. 1) on November 25, 1980. (Also given in the top of Fig. 3-c). Units: %.

Quantities		Depth (m)				
		1	2	4	6	8
Computed I	RE_{TW}	27.7	14.4	4.9	1.9	0.8
	RE_{PW}	54.4	30.7	10.8	4.2	1.7
	RE_Q	54.3	30.6	10.7	4.2	1.7
	RE_I	63.7	41.1	17.1	7.4	3.2
II	RE_{TW}	20.9	8.6	1.9	0.5	0.1
	RE_{PW}	41.5	18.4	4.1	1.1	0.3
	RE_Q	41.6	18.5	4.2	1.1	0.3
	RE_I	51.1	26.4	7.4	2.1	0.6
Measured	RE_{TW}	42.0	26.4	7.5	2.2	—
	RE_Q	58.2	34.3	13.7	4.9	2.1
	RE_I	72.7	59.1	20.9	10.0	4.7

wave portion of this spectral region (700-2500 nm), which contains a large portion of energy (i.e., approximately equal to the energy of the 400-700 nm spectral block; see Table 4), is immediately absorbed by a thin surface layer of water. The amount of energy in the wavelength region below 300 nm is negligible.

Our calculations also indicated that RE_{PW} was virtually equal to RE_Q at any given

depth up to 8 m deep (I and II in Table 5). This is because the shorter wavelength portion of the 400-700 nm band penetrates equally well as the longer wavelength portion in the water of this particular lake (Table 4).

3-2. Other Lakes and Marine Environments

Now this analysis and discussion are extended to other natural waters to obtain a more generalized picture of the differ-

Table 6. Attenuation coefficients for blue (k_B), green (k_G) and red (k_R) light were obtained in various English lakes and Scottish lochs along with those in Lake Biwa. Data for code nos. 1-14 are adopted from Table 5.2 in SPENCE (1975). For Lake Biwa I and II, the coefficients were estimated from curves I and II of Fig. 4, respectively; k_B , k_G and k_R being the average attenuation coefficients over the waveband of 400-500 nm, 500-600 nm, and 600-700 nm, respectively.

Code no.	Lake or loch	Date	k_B	k_G	k_R	Depth of euphotic zone (m)
			(m ⁻¹)			
1.	Lochan an Eun	Jul. 1969	0.14	0.12	0.33	30.8
2.	Wastwater	Jun.-Sep. 1952	0.18	0.12	0.38	30.8
3.	Ennerdale Water	Jun.-Sep. 1952	0.25	0.13	0.31	28.7
4.	Borrallie	Jun. 1971, 1972, 1974	0.29	0.16	0.45	23.0
5.	Croispol	Jun. 1971, 1974	0.29	0.18	0.43	20.8
6.	Derwentwater	Jun.-Sep. 1952	0.47	0.32	0.42	11.6
7.	Windermere South	Jun.-Sep. 1952	0.66	0.35	0.58	10.4
8.	Uanagan	Jul. 1967	0.62	0.37	0.43	10.0
9.	Lanlish	Aug. 1974	0.77	0.36	0.56	10.2
10.	Esthwaite Water	Jun.-Sep. 1952	0.77	0.48	0.52	7.6
11.	Clunie	Jun. 1967	0.84	0.46	0.47	8.0
12.	Lowes	Jul. 1967	0.97	0.60	0.59	6.2
13.	na Thull	Jun. 1974	1.19	0.55	0.54	6.7
14.	Leven	Sep. 1974	2.01	1.07	1.04	3.5
	Lake Biwa I	Oct. 1975	0.74	0.42	0.76	
	Lake Biwa II	Dec. 1976	1.11	0.65	1.02	

ences in irradiance penetration owing to the differences of expressions or units. Lakes of various optical water types (Table 6), as reported in SPENCE (1975), will be first looked at. In doing so, we simplify the analysis by splitting the visible range of radiation (400-700 nm) into three wavelength blocks (cf., nine in the previous analysis): 400-500 nm, 500-600 nm, and 600-700 nm, which approximately represent blue, green and red, respectively. Corresponding energy contents in each block $\hat{E}_i$ are thus 143, 144 and 131 W·m⁻² (from Table 4), and corresponding average attenuation coefficients k_i are assumed to be k_B , k_G and k_R in Table 6. Average spectral sensitivity over 100 nm waveband S_i was estimated from the data in Fig. 2 for illuminance, quanta and energy. RUI ($D=1$ m) for these three expressions was then computed with eq. (2).

Results thus obtained (Table 7) clearly show that, in terms of illuminance (RE_i),

RUI was greater than either in terms of quanta (RE_Q) or energy (RE_{PW}) for all the lakes of various optical properties.

Roughly speaking, $\hat{E}_i$ in the visible region is sensed equally well with the quantum and pyranometer sensors, whereas the photometric sensors are much more sensitive to the green light. At the same time, $\hat{E}_i$ in this region is more or less flat in the atmosphere. Accordingly, RE_i is primarily determined by k_G , whereas RE_Q and RE_{PW} are determined by the average attenuation coefficient for the whole visible region. In other words, RUI ($D=1$ m) can be approximated as

$$RE_i \approx \exp(-k_G) \quad (3)^*$$

$$RE_{PW} \text{ (or } RE_Q) \approx \frac{\exp[-(k_B + k_G + k_R)/3]}{\exp[-(k_B + k_G + k_R)/3]} \quad (4)^{**}$$

* This relation holds exactly when S_i (see eq. 2) for both blue and red regions are equal to zero.

** When $S_i E_i$ is the same for blue, green and red regions, RE_{PW} (or RE_Q) = $[\exp(-k_B) + \exp(-k_G) + \exp(-k_R)]/3$ which can be approximated as eq. (4) when $k_B \approx k_G \approx k_R$.

Table 7. Comparisons of relative underwater irradiance at 1 m depth as lux (RE_I), quanta (RE_Q) and energy (RE_{pw}) in the wavelength range 400-700 nm for various fresh water. Computed with data given in Table 6. Units: %.

Lake or loch Code no.	RE_I	exp ($-k_G$)	RE_Q	RE_{pw}	exp $[-(k_B+k_G+k_R)/3]$
1.	86.0	88.7	82.1	82.9	81.9
2.	85.2	88.7	79.9	80.7	79.7
3.	84.8	87.8	79.8	80.0	79.5
4.	81.2	85.2	74.6	75.1	74.1
5.	80.0	83.5	74.3	74.9	74.1
6.	70.7	72.6	67.3	67.1	66.8
7.	66.8	70.5	59.9	59.7	58.9
8.	67.2	69.1	63.3	62.7	62.3
9.	65.9	69.8	58.6	58.0	56.9
10.	60.2	61.9	56.6	55.9	55.4
11.	61.4	63.1	57.4	56.3	55.4
12.	53.6	54.9	50.4	49.4	48.7
13.	55.5	57.7	50.4	48.8	46.8
14.	32.7	34.3	28.8	27.6	25.4
Lake Biwa I	61.4	65.7	53.8	53.8	52.7
Lake Biwa II	48.2	52.2	40.9	40.8	39.6

which are confirmed by our calculations (Table 7). Since the attenuation coefficient for green light (k_G) is always much smaller than the average attenuation coefficient for the entire visible region $[(k_B+k_G+k_R)/3]$, as seen from Table 6, the illuminant flux must be attenuated less than the energy or the quantum flux. However, SMITH *et al.* (1973) used spectral irradiance measurements at various depths and found that the theoretical attenuation coefficient for illuminance was slightly greater than that for energy flux for both Crater Lake and Lake Tahoe, both very transparent lakes. Thus, it appears that the illuminant flux attenuates slightly more rapidly than the energy or the photon flux in waters of extreme transparency.

The distinction between attenuation of irradiance in terms of energy and of quanta was more complicated: The magnitude and direction of differences between penetrations of quantum and energy varies with the optical properties of waters (Table 7). In waters where $k_G \leq k_B < k_R$ (lakes 1-5 in Table 6), RE_Q was slightly smaller than RE_{pw} . In contrast, the opposite tendency

was seen in waters where $k_G \leq k_R < k_B$ (lakes 8-14 in Table 6). In waters having similar k_B and k_R (lakes 6 and 7 as well as Lake Biwa in Table 6), attenuation of quanta is approximately equal to that of energy. A similar result was obtained earlier from more detailed computations in Lake Biwa. For rough estimation, one could use the depth of the euphotic layer: RE_Q approximately equals RE_{pw} in lakes having a euphotic layer of about 10 m, and RE_Q is smaller than RE_{pw} in more transparent lakes but vice versa in more turbid lakes. Similar results were obtained by LEWIS (1975), who, on theoretical grounds, demonstrated that the opposing effects of pure water and dissolved color would be balanced in a waterbody with a Pt color of 5.5 - 6.5 so that attenuation of quanta is approximately equal to that of energy. This kind of systematic deviation between penetration of quanta and energy, which is dependent on the magnitude of the attenuation coefficient of the shorter wavelength portion of the 400-700 nm band relative to that of the long-wave portion, can be expected since the number of quanta per

Table 8. Mean attenuation coefficients for blue (k_B), green (k_G) and red (k_R) light in various sea waters. Computed from Table 17 in JERLOV (1976); as for Lake Biwa, in Table 6. I-III: oceanic types. 1-9: coastal types. Units: m^{-1} .

Optical water types	k_B	k_G	k_R
I	0.023	0.091	0.376
IA	0.030	0.096	0.385
IB	0.041	0.102	0.390
II	0.075	0.122	0.414
III	0.142	0.159	0.459
1	0.286	0.168	0.456
3	0.444	0.230	0.492
5	0.646	0.340	0.574
7	0.996	0.494	0.670
9	1.624	0.716	0.806

energy increases linearly with increasing wavelength (PLANCK's law or from the spectral response function of the quantum sensors as given in Fig. 2-b).

Similar analysis and discussion can be made with marine environments, data for which (Table 8) were derived from JERLOV (1976). Inspection of Table 8 indicates that $k_G < (k_B + k_G + k_R)/3$ for all waters under consideration. The illuminant flux therefore attenuates the least in these waters as in lakes previously discussed. In waters of optical types I-III (oceanic water types) and type 1, RE_Q is expected to be smaller than RE_{PW} as k_B is smaller than k_R . The reverse would be true in waters of optical types 5, 7 and 9 (coastal water types) where k_B is greater than k_R . In waters of optical type 3 where k_B is approximately equal to k_R , RE_Q should be similar to RE_{PW} .

Mathematically, the ratio E_{PW}/E_Q is an exponential function of $(k_e - k_q)$, where E_{PW} and E_Q are the energy flux density and the photon flux density in the range of 400-700 nm, and k_e and k_q are the attenuation coefficients for the energy flux density and the photon flux density in the same range, respectively. The result that the ratio E_{PW}/E_Q approaches a constant value with increas-

ing depth for each water type (JERLOV and NYGÅRD, 1969; MOREL and SMITH, 1974) may therefore be a result of the more or less constant nature of both k_e and k_q with depth. Thus, our discussion based on the computation of RUI at $D=1$ m would be equally valid for underwater irradiances below 1 m depth. It is obvious without computation that the attenuation of energy in the spectral band 300-2500 nm is more rapid than other quantities in other lakes and marine waters just as in Lake Biwa. SVERDRUP *et al.* (1942) theoretically demonstrated years ago that in pure water the total energy in the range of 350-2500 nm attenuated more rapidly than the energy in the visible part of the spectrum (which means that RE_{PW} was much smaller than RE_{TW} at all depths in the water column).

4. Conclusions

Our measurements and computation of underwater irradiance demonstrated that there are systematic and significant deviations among penetration of illuminance, energy and quanta. Irradiance as measured or expressed as energy in the 300-2500 nm spectral band attenuates most rapidly in waters of any optical properties, since the longer wavelength portion of this spectral band, which contains approximately half the total energy of the whole spectral band, is absorbed rapidly by a thin surface layer of water. For the 400-700 nm spectral band, the illuminant flux is generally the least attenuated because of selective transmittance of green light that is most readily sensed by photometric sensors. Though the differences in penetration of energy and quanta are small, they are systematic and predictable, depending on the optical properties of waters. In transparent waters, the attenuation of quanta will be more rapid than that of energy, since such waters absorb the longer wavelength portions selectively and the number of quanta increases with wavelength. The opposite is to be expected in waters of high dissolved color, where the shorter wavelength portion of visible radiation is

more strongly absorbed. In waters of intermediate transparency, such as Lake Biwa, the attenuation of quanta is approximately equal to that of energy.

The dangers of using photometric units for processes other than the response of the human eye have been pointed out repeatedly by many scientists (e. g., TYLER, 1973 a, 1973 b). Phytoplankton, for instance, are much more sensitive to blue and red lights than the human eye, which is predominantly sensitive to green light. Therefore, errors as high as 600-700% can arise if photometric measurements are used to determine the relevant radiant energy associated with photosynthesis (TYLER, 1973 b). Our study again demonstrates that irradiance in lux significantly deviates from irradiance as photon flux density in the range of photosynthetically active wavelength. We, therefore, urge those who have remained with photometry in the study of primary production to shift to quanta or energy measurements in the range of the photosynthetically active wavelength.

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摘 要

琵琶湖において、水中放射束密度の垂直分布を照度、光合成有効波長域 (400-700 nm) の光子束密度および全短波長域 (300-2500 nm) のエネルギー束密度の3者で同時に測定した。水中放射の減衰は全短波エネルギー単位が最も急速で以下、光子束密度、照度の順であった。そして、この測定結果は琵琶湖について報告されている分光放射の測定資料と3つの放射センサーの分光感度特性を用いて計算した結果と定性的に一致した。したがって、照度、光子束密度およびエネルギー束間でその減衰に前述のような違いが観測されたのはセンサーの分光感度特性の違いと琵琶湖水体の分光透過特性とに基づくものと考えられる。なお、計算では光合成有効波長域のエネルギー束についてもその減

衰を調べたところ、光子束の減衰とほとんど同じであることが見いだされた。

さらに、琵琶湖以外の湖や海についても文献に報告されている資料を用いて同様の理論的解析を行い、水中相対放射束密度 (RUI) を照度の場合 (RE_I)、光合成有効波長域光子束密度の場合 (RE_Q)、同波長域エネルギー束の場合 (RE_{PW}) および全短波長域エネルギー束の場合 (RE_{TW}) で比較した。そして、一般的に

(1) 赤外線以上の長波放射はどの水界でも表層でほぼ完全に消滅するので、 RE_{TW} は他の3つの RUI より小さくなる。

(2) 単位エネルギー束密度当り光子束密度が長波光ほどやや高いという光子センサーの感度特性と結びついて、①水中放射減少率の低い水界では長波光ほどより顕著に減少するため $RE_Q < RE_{PW}$ 、②この減少率の高い水界では逆傾向のため $RE_Q > RE_{PW}$ 、③中程度の減少率の水界では長波光と短波光とが同程度に減少するため $RE_Q \approx RE_{PW}$ となる。

(3) ほとんどの水界では緑色光域の水中減光率は他の波長光域の平均的減光率より小さく、また照度センサーはこの緑色光に選択的に感応するため、 RE_I が最大となる。

と結論した。また、この結論に基づいて、水界一次生産の研究のためには照度計による放射測定は非常に危険であることが指摘された。

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