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RELATIONS BETWEEN TOTAL QUANTA BLUE IRRADIANCE AND SECCHI DISC OBSERVATIONS IN THE NORWEGIAN AND BARENTS SEAS

by

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Abstract

Linear relations between integrated quanta irradiance and blue irradiance are presented. The range of the euphotic zone is about three times the Secchi disk depth in these waters.

Introduction

Photosynthesis is proportional to quanta number rather than to energy, and since the photosynthetic active part of the daylight spectrum extends from about 350 to 700 nm, the integrated quanta irradiance in this range will often be the optical property which is of most interest to the biologist.

For some time commercially manufactured quanta meters (Lambda Instruments Co.), which measure in range 400 - 700 nm, have been available. These instruments seem to work well, but from my experience they are less light sensitive than the simple irradiance meters which consist of selenium cells with glass filters and opal glass. The latter type can be used to greater depths, and for certain studies this property is advantageous. It then becomes worthwhile to seek for ways of calculating integrated quanta irradiance by means of the simple irradiance meter.

Jerlov (1974) has given a formula for the relationship between blue irradiance and integrated quanta irradiance, which is valid for clear or bluish ocean waters. But the colour of the waters of the Norwegian and Barents Seas varies from blue to green, and the mentioned formula is then not of general validity here. In an earlier analysis of irradiance observations from these areas Aas and Berge (1976) obtained a relation which seemed useful, and this relation will now be extended and discussed with more details.

The Secchi disk is still perhaps the most applied optical device in oceanography, although certainly not the most highly estimated. This undeserved fate is due to the complex relationship which exists between the depth of disappearance and the optical properties of the water and the sea surface, which makes it difficult to establish simple formulae of general validity, if a reasonable accuracy is required. For more limited areas, however, it seems as if the Secchi disk may serve as a valuable complement to other optical measurements. In the final part of this work the integrated quanta irradiance will be compared with the Secchi disk observations.

The observations

At 17 of the stations from the Norwegian and Barents Seas, irradiance was measured with broad-band filters in all parts of the visible spectrum. The integrated quanta irradiance Q could then be obtained either from calculated spectral irradiance distributions, or directly from the photocurrents by means of an earlier obtained correlation formula of the type

$$Q = K_1U + K_2B + K_3V + K_4R \qquad (1)$$

U, B, V and R are photocurrents measured in the ultraviolet, blue, green and red part of spectrum, and the K's are correlation constants. The difference between the two methods has been found to be less than 2% (Aas, 1971). The applied spectral range of Q in 1976 was 350 - 750 nm. Jerlov (1974), however, uses the recommended range 350 - 700 nm (SCOR, 1974), and this is of some importance for the surface value. The ratio Q (350 - 700 nm)/Q (350 - 750 nm) is 0.90 ± 0.04 at the surface of the present stations. Beneath the surface the ratio soon becomes 1. The transmittances of Q presented in 1976, have been recalculated here to the range 350 - 700 nm, in order to make a comparison with Jerlov's results easier.

The earlier analysis demonstrated that the photocurrent B, measured with the Schott filters B12 + G5, was proportional to the irradiance at 465 nm (Aas and Berge, 1976, Fig. 4). The irradiance transmittance at 465 nm can then be calculated directly from the observed photocurrent B.

At some of the Secchi depth stations only the photocurrent B was observed. Q has then been estimated by the method which is going to be described.

The Secchi depth and the transmittance of Q and B are presented in Table

1. The locations of the stations and other data were given in 1976. Due thanks are given to the Institute of Marine Research, Bergen, for the generous supply of the Secchi disk observations.

The relation between integrated quanta irradiance and blue irradiance

Jerlov (1974) found for clear oceanic waters that

$$T_Q = T_B(0.23 + \frac{5.6\ m}{7.3\ m + z}) = T_B\ f(z) = e^{-Kz} f(z) \qquad (2a)$$

T_Q and T_B are the transmittances of integrated quanta irradiance Q and blue irradiance B, between the surface and the depth z. K is the vertical attenuation coefficient of blue irradiance at 465 nm.

Taking the natural logarithm at each side of the equation, we obtain

$$\ln T_Q = \ln T_B + \ln f(z) = -\ Kz + \ln f(z) \qquad (2b)$$

If we plot T_Q on a logarithmic axis and K on a linear axis, the relation between T_Q and K should be a straight line for each depth z.

However, the results in 1976 gave another picture. Fig. 1 shows that the relationship between integrated irradiance and the vertical attenuation coefficient at 465 nm rather seems to consist of two sets of straight lines, one for values of K less than 0.1 m^{-1}, and another for K greater than 0.1 m^{-1}. (Integrated energy irradiance in the range 350 - 750 nm was used rather than integrated quanta irradiance in the range 350 - 700 nm, but the difference between the transmittances is small).

This optical division coincides with Jerlov's division between oceanic and coastal water types, based upon K at 465 nm (Jerlov, 1976, Fig. 71). It also coincides with the division that we made in 1976 from the horizontal distributions of salinity and optical properties. In these distributions the Atlantic waters seemed to separate from the surrounding waters by having a vertical attenuation coefficient less than 0.1 m^{-1}. (It should be noted, however, that the isolines did not coincide exactly, and when the optical properties were plotted as functions of salinity, more confusing pictures resulted. This problem has been commented further upon by Neuymin and Sorokina (1978) and by Aas (1979)).

For K = 0.1 m^{-1}, eq. 2a gives at the depths 5, 10, 20, 30, 40 and 50 m that T_Q should be 42, 21, 6.2, 1.9, 0.64 and 0.22% respectively, while Fig. 1 gives the values 40, 20, 5.0, 1.6, 0.63 and 0.24%. But this fairly good agreement is lost for greater values of K.

To determine T_Q from observations of T_B, one may then use Fig. 1, or try to construct from it formulae like eq. 2, for values of K smaller and greater than 0.1 m^{-1}. A difficulty in the theoretical approach is caused by the fact that the waters at many of the stations are not optically homogeneous. This problem seems to be avoided if one looks at the depths Z_Q and Z_B where

$$T_Q(Z_Q) = T_B(Z_B). \tag{3}$$

The linear relation

$$Z_Q(1\%) = (7 \pm 2)m + (0.67 \pm 0.04) Z_B(1\%) \tag{4a}$$

was found to be valid with a correlation coefficient r = 0.98 (Aas and Berge, 1976). The method may be extended to other T values, and the results become:

$$Z_Q(3\%) = (5 \pm 1)m + (0.66 \pm 0.04) Z_B(3\%) \tag{4b}$$

$r = 0.98$

$$Z_Q(10\%) = (3 \pm 1)m + (0.63 \pm 0.03) Z_B(10\%) \tag{4c}$$

$r = 0.98$

$$Z_Q(30\%) = (1.7 \pm 0.4)m + (0.56 \pm 0.04) Z_B(30\%) \tag{4d}$$

$r = 0.96$

An approximated general formula, which lies within the calculated uncertainties above, is

$$Z_Q(T) = (7m)(T/0.01)^{-0.4} + (0.67-0.4T) Z_B(T) \tag{5}$$

For T = 0.01 the formula reduces to eq. 4a. The uncertainty of Z_Q as a function of Z_B is about 9%.

The observations and the straight lines from eqs. 4 are presented in Fig. 2, where Jerlov's optical ocean water types (Jerlov, 1976, Fig. 71, 1977, table 2) have been included. It is seen that the lines coincide with the ocean water types when T is 1 and 3%, but deviate closer to the surface, when T is 10 and 30%.

The deviations from the ocean water types also become apparent when the 1, 3 and 30% levels of Q are correlated with the 10% level. Jerlov (1977) has obtained the relations

$$Z_Q(30\%) = 0.50\ Z_Q(10\%) - 0.0023\ Z_Q^{\,2}(10\%) \tag{6a}$$

$$Z_Q(3\%) = 1.65\ Z_Q(10\%) \tag{6b}$$

$$Z_Q(1\%) = 2.18\ Z_Q(10\%) \quad (6c)$$

for ocean water types I-III and coastal water types 1-3. The present observations (Fig. 3) give:

$$Z_Q(30\%) = (0.3 \pm 0.4)\text{m} + (0.46 \pm 0.03) Z_Q(10\%) \quad (7a)$$

$r = 0.98$

$$Z_Q(3\%) = (0 \pm 1)\text{m} + (1.68 \pm 0.07) Z_Q(10\%) \quad (7b)$$

$r = 0.99$

$$Z_Q(1\%) = (1 \pm 2)\text{m} + (2.4 \pm 0.1) Z_Q(10\%) \quad (7c)$$

$r = 0.98$

The deviations from Jerlov's results, although small, are probably real and due to the earlier mentioned inhomogenities at our stations, which are mostly caused by differences in particle concentration with depth.

The relation between integrated quanta irradiance and Secchi disk depth

When the white Secchi disk disappears from sight, it has the same colour as the sea around it, and this colour corresponds to the wavelength of maximum irradiance transmittance. It then seems reasonable that the Secchi disk depth and the optical properties at the wavelength of maximum transmittance are linked together in some way. And conversely, if Secchi disk observations from regions of different water colours are compared with their corresponding optical properties at a fixed wavelength, rather confusing pictures are likely to result. Højerslev (1976, 1977) avoids this problem very cleverly by observing the Secchi disk through a colour filter of the same type as in the optical instrument. The present observations, however, were made with the naked eye although the colour of the sea at the different stations varied from blue to green. Still, as will be shown, the results may be of some use.

Poole and Atkins (1929) discovered from observations in the English Channel that the product of the vertical attenuation coefficient of blue irradiance, K, and the Secchi disk depth, D, varied less than K and D themselves. The mean value of the product was

$$K \cdot D = 1.7 \quad (8)$$

The standard deviation was 0.3. The authors did not claim that this result should be of general validity for all oceans, but textbooks often refer to it as if it were, and mostly without any reference to the wavelength of K. Neither has it been noted that K was the attenuation coefficient between 0 and 20 m, while D had values between 6.5 and 22 m. If the value of K between the surface and the Secchi depth is applied, another result will be obtained, as shown in Table 2. Still some authors (Idso and Gilbert, 1974) claim that eq. 8 does possess a universality.

Recent theoretical relations between the Secchi depth and the optical properties have been worked out and discussed by Tyler (1968) and Højerslev (1976, 1977). If one assumes that there is a constant ratio between the absorption and scattering coefficients, it is possible to obtain from these theories relations similar to eq. 8.

If

$$K \cdot D = \text{constant}, \tag{9}$$

the transmittance between the surface and the Secchi depth becomes

$$T_B(D) = e^{-KD} = \text{constant} \tag{10}$$

If we then study the values of z for which the different $T_B(z)$ have a constant value, we obtain frcm

$$T_B(z) = e^{-Kz} = (e^{-KD})^{z/D} = (T_B(D))^{z/D} \tag{11}$$

that these values $z = Z_B$ should follow

$$Z_B/D = \ln T_B(Z_B)/\ln T_B(D) = \text{const./const.}, \tag{12}$$

that is, there should be a constant ratio between Z_B and D.

Our results yield

$$Z_B(30\%)/D = 0.9 \pm 0.3 \tag{13a}$$

$$Z_B(10\%)/D = 1.7 \pm 0.5 \tag{13b}$$

$$Z_B(3\%)/D = 2.7 \pm 0.8 \tag{13c}$$

$$Z_B(1\%)/D = 3.3 \pm 0.8 \tag{13d}$$

These values are plotted in Fig. 4. Although the standard deviations of the ratios $Z_B(T)/D$ are great, as predicted from the variation of the water colour at our stations, the mean values may be fairly well approximated by the equation

$$T_B = 0.01^{Z_B/3.4D} \tag{14}$$

or

$$Z_B = 3.4\ D\ \ln T_B/\ln 0.01 \tag{15}$$

By means of eq. 5, we now obtain

$$Z_Q(T) = 7\ m\ (T/0.01)^{-0.4} + (0.67-0.4T)3.4D\ \ln T/\ln 0.01 \tag{16}$$

In view of the great variation of the ratios in eqs. 13, this equation is unnecessary complicated. A simpler expression is obtained directly from the ratios Z_Q/D. Their mean values and standard deviations are

$$Z_Q(30\%)/D = 0.7 \pm 0.2 \tag{17a}$$

$$Z_Q(10\%)/D = 1.5 \pm 0.3 \tag{17b}$$

$$Z_Q(3\%)/D = 2.3 \pm 0.5 \tag{17c}$$

$$Z_Q(1\%)/D = 3.3 \pm 0.7 \tag{17d}$$

These values are plotted in Fig. 5. It is seen that a rough but simple relation between T_Q and Z_Q/D is

$$T_Q = 0.01^{Z_Q/3D} \tag{18}$$

or

$$Z_Q = 3\ D\ \ln T_Q/\ln 0.01 \tag{19}$$

The uncertainty of Z_Q as a function of D is 20-30%. But in rough weather direct irradiance measurements may have the same uncertainty. So if such measurements are lacking, a straight line in a semi-logarithmic diagram through the points T_Q = 100%, Z_Q = 0 m and T_Q = 1%, Z_Q = 3 D will give a quite useful description of the quanta irradiance attenuation in the euphotic zone. If $Z_Q(1\%)$ is taken as the lower limit of the euphotic zone, this depth will be about three times the Secchi depth.

As already hinted at, I think that the principally correct procedure is to observe the Secchi disk through the same filter as in the optical instrument, as proposed by Højerslev. If the Secchi disk is observed with the naked eye and the water alone is acting as a filter, as in the present observations, two different spectra will influence the visibility of the Secchi disk. One is due to the reflected light from the surface, and another to the upward scattered light from the sea. The relative magnitude of the spectra is related to the spectral sensitivity of the human eye, and the light should be measured in photopic units (illuminance) rather than in energy or quanta units (irradiance). But this does not mean that it is correct to compare the Secchi disk depth with the attenuation of downwelling illuminance. The eye does not tend to compare the light from the Secchi disk with the broad-spectered or "white" illuminance incident at the surface, but tries to compare it with the upwelling light from the sea, which has a much narrower spectrum and a definite colour (Williams, 1970). Principally one should then measure either upwelling illuminance, or downwelling illuminance in a narrow spectral region around the wavelength of maximum transmittance, since the attenuation of the last quantity probably is very similar to the first one's.

In addition to the upwelling coloured light from the water, the eye will receive reflected "white" light from the surface. This light will be of the same order of magnitude as the upwelling light, and it will disguise the contrast between the Secchi disk and its surroundings. The simple relation given by eq. 9 does not take into account the last effect.

The eqs. 13 and 17 give better correlation between Z_Q and D than between Z_B and D at our stations. This indicates that it is better to estimate quantities like downwelling illuminance and integrated irradiance from Secchi disk observations, than to estimate irradiance at a fixed wavelength, if the waters are of varying colours. The reason may be that the transmittance of the integrated quantities will approach the maximum transmittance with increasing depth, while the transmittance at the fixed wavelength may become more and more different from the maximum transmittance.

When wind or waves increase, the Secchi depth will decrease (Gall, 1949, Joseph, 1952, Beeton, 1957, Højerslev and Lundgren, 1977). Our observations give that when the sea has waves in the range 0-0.5 m (state of sea: 0-2),

$$Z_Q(10\%)/D = 1.4 \pm 0.3 \qquad (20)$$

while with waves in the range 0.5 - 2.5 m (state of sea: 3-4), the ratio becomes

$$Z_Q(10\%)/D = 1.6 \pm 0.3 \qquad (21)$$

The uncertainty regions overlap, so this effect has not been taken into account in the present analysis.

Some observations from different waters are presented in Table 2. Other references are given by Strickland (1958). In many cases it is not clear to what extent the immersion effect of the irradiance meter has been taken into account.

The irradiance observations by Seglem in Table 2 were performed with a B12 + G5 filter, but without any opal glass, and this may have affected the vertical attenuation. His values are, however, remarkably similar to the present results. It is also seen from the table that there is much less variation in the relation between blue irradiance and Secchi depth in the English Channel and the North Sea, than in the Norwegian and Barents Seas.

Højerslev (1978) points out that lux and integrated quanta will be attenuated to about the same degree in the oceans. This may be the reason why the illuminance and quanta relations vary approximately within the same limits in Table 2. (The values attributed to Graham are calculated from mean values of D and K, and not from mean values of D·K. The values calculated from Højerslev and Lundgren's observations comprise only four stations).

It seems evident from the present results that the Secchi disk, when used properly, may serve as a valuable complement to the quanta irradiance meter.

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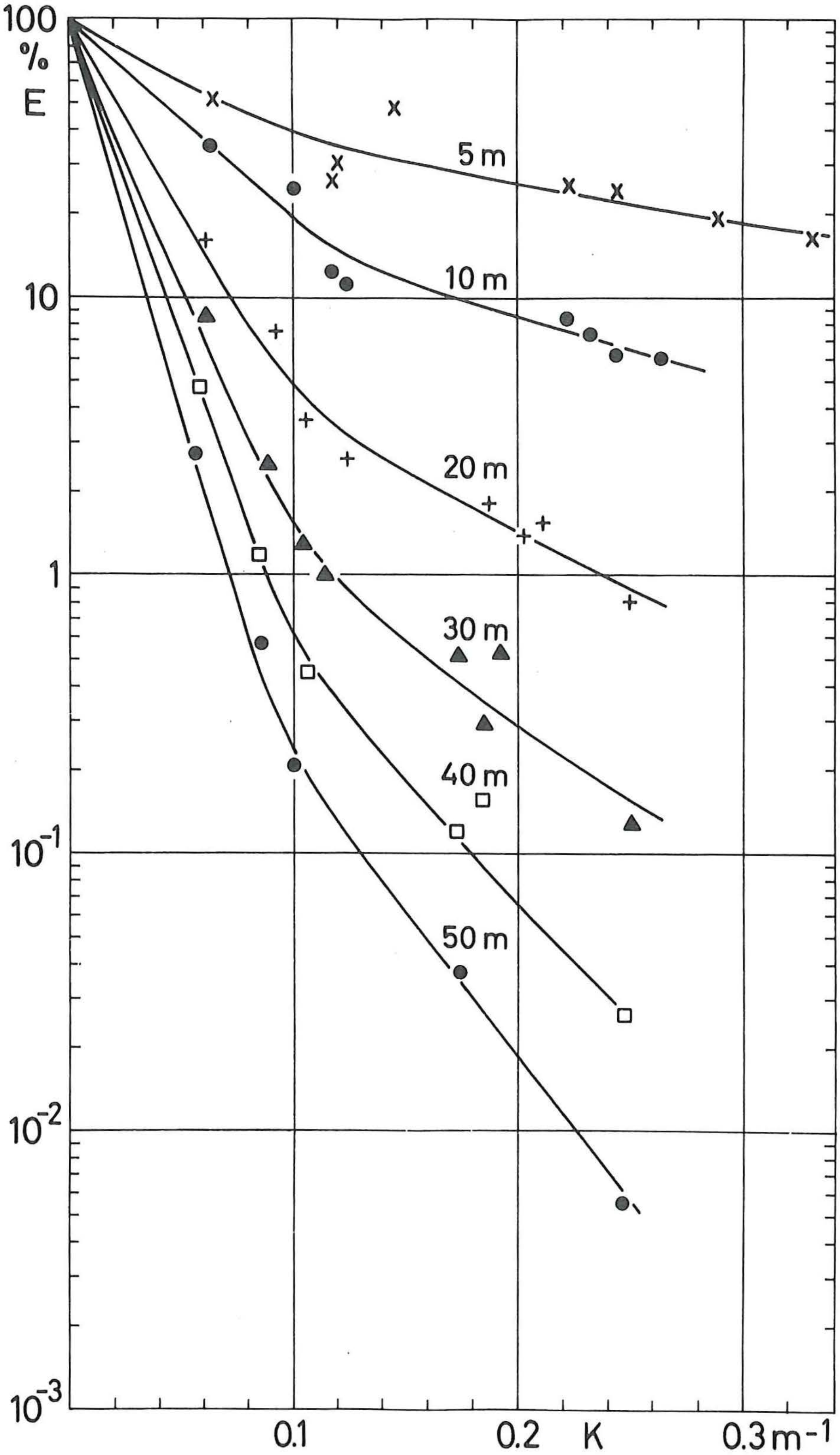

Fig. 1. Integrated irradiance E(350-750 nm) in percent of its surface value, as a function of the vertical attenuation coefficient K at 465 nm for different depths (Aas and Berge, 1976).

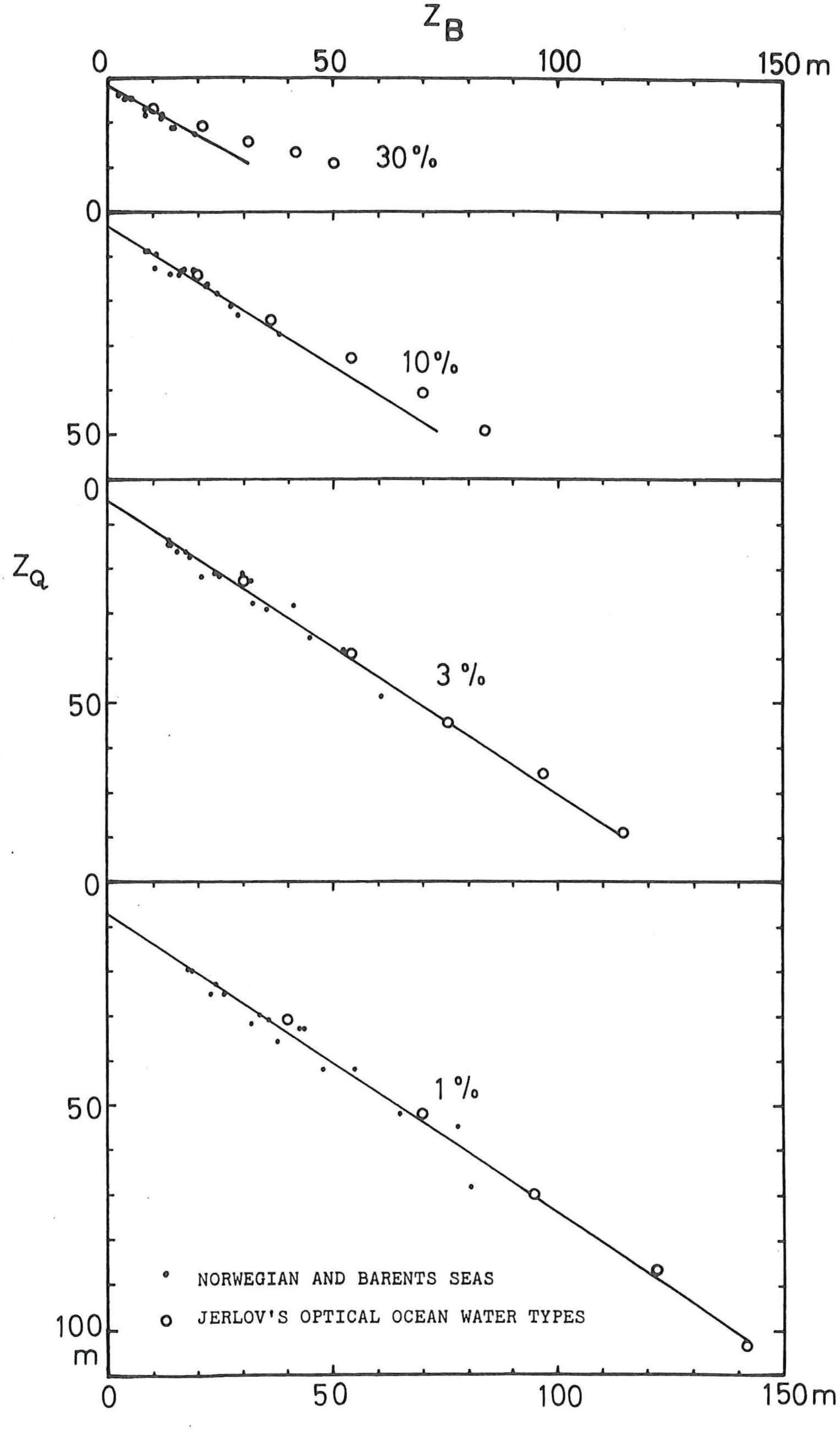

Fig. 2. The depth of integrated quanta irradiance, Z_Q, as a function of the depth of blue irradiance, Z_B, for the transmittance values 30, 10, 3 and 1%.

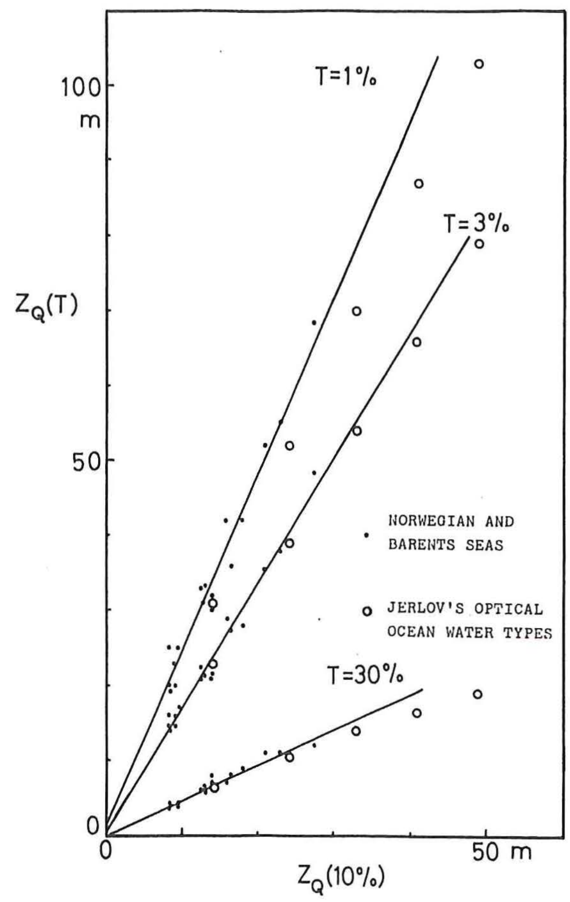

Fig. 3.
The transmittance levels Z_Q (30%), Z_Q(3%) and Z_Q(1%) of integrated quanta irradiance, as a function of the 10% level Z_Q(10%).

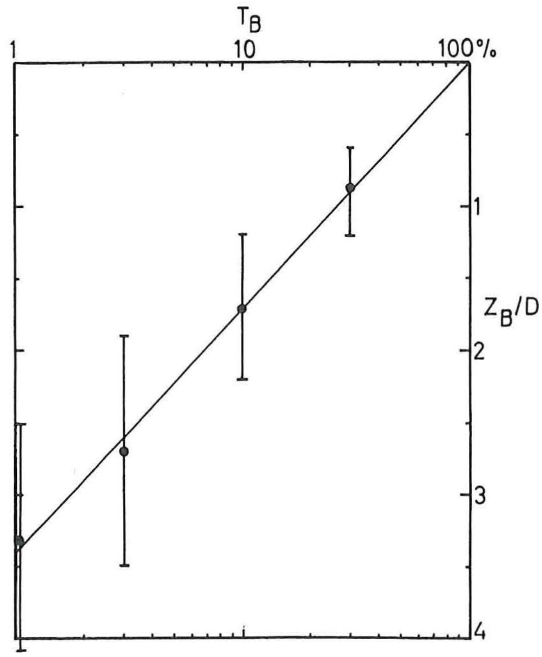

Fig. 4.
The ratio between the transmittance level Z_B of blue irradiance and the Secchi depth D, as a function of the blue irradiance transmittance T_B.

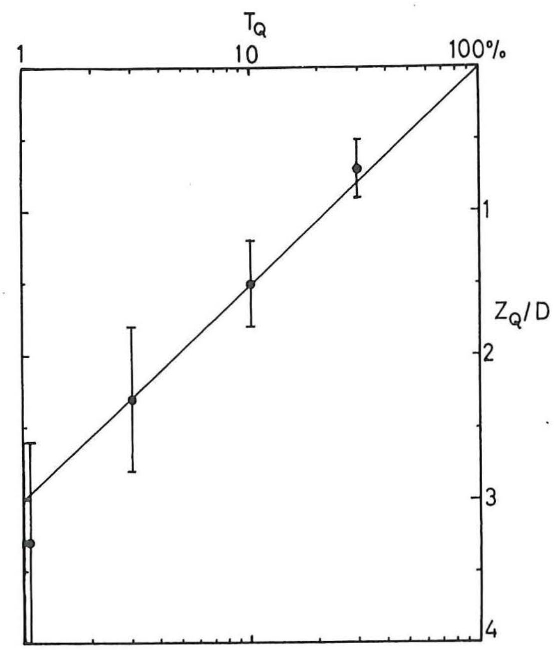

Fig. 5.
The ratio between the transmittance level Z_Q of integrated quanta irradiance and the Secchi depth D, as a a function of the irradiance transmittance T_Q.

TABLE 1.

Station	Year	Secchi disk depth	Sea	T	5 m	10 m	20 m	30 m	40 m	50 m
166	1958	10	4	Q"	43	21	4.6	0.75		
				B	54	40	9.2	1.44		
178	"	10	3	Q"	50	25	10.0	1.65	0.38	
				B	45	33	20	6.7	(0.55)	
232	"	18	2	Q"	55	30	13.0	5.0	2.1	0.94
				B	56	39	20	11.3	4.6	2.2
244	"	12	1	Q"	44	21	6.6	1.85	0.44	
				B	53	32	10.6	4.2	0.95	
256	"	15	1	Q"	42	21	8.0	3.5	1.90	1.08
				B	45	30	11.4	5.1	3.2	2.0
323	"	10	3	Q"	46	23	6.2	2.0	0.75	
				B	71	40	10.3	4.0	(1.58)	
336	"	5.5		Q"	24	7.5	0.85			
				B	24	7.4	(0.43)			
346	"	6.5	0	Q"	30	12.0	1.90	0.40		
				B	37	14.3	2.28	(0.36)		
368	"	8.5	3	Q"	47	22	3.6	0.75		
				B	50	29	7.1	1.14		
a	1967		3	Q	51	26	7.5	2.4	1.14	0.56
				B	47	36	14.5	6.4	3.2	1.45
b	"		4	Q	34	13.6	3.9	1.37		
				B	54	28	10.4	3.8		
c	"		1	Q	18.2	6.8	1.65	0.58	0.167	
				B	34	18.4	7.1	1.48	0.41	0.097
161	1968		1	Q'	23	6.8	1.02	0.31	0.130	0.061
				B	29	8.4	0.73	0.176	0.083	0.041
172	"		2	Q	27	8.9	1.89	0.54	0.123	0.039
				B	34	11.4	2.4	0.58	0.116	
201	"		2	Q	34	14.4	3.3	1.28	0.55	0.26
				B	52	29	7.3	2.9	1.35	0.62
403	1969	10	3	Q"	46	21	4.6	1.66	0.73	
				B	54	29	7.9	2.2	1.09	0.57
418	"	9	3	Q'	39	16.2	3.7	1.06	0.49	0.22
				B	49	25	6.1	1.51	0.77	0.40
429	"	9	2	Q'	52	19.2	3.6	1.19	0.45	0.190
				B	53	23	3.4	1.24	0.44	0.192
430	"	13	2	Q"	46	23	6.0	1.75	0.58	
				B	57	33	10.4	3.6	1.17	0.47
443	"	10	1	Q"	42	22	7.5	2.7	1.26	0.58
				B	54	32	11.4	5.1	2.3	1.21
450	"	15	2	Q'	45	20	6.5	2.3	0.57	0.088
				B	62	38	13.8	4.7	0.68	0.084
457	"	8	2	Q	25	6.6	0.84	0.136	0.028	0.0059
				B	28	8.0	0.64	0.053	.0059	.00066
470	"		3	Q'	40	19.3	6.6	2.7	1.19	0.51
				B	56	33	12.5	5.1	1.96	0.79
d	1971	8	3	Q'	24	7.0	0.95	0.163		
				B	23	6.8	0.65	0.074		
249	"	10	4	Q'	41	18.9	3.4	1.02	0.39	0.150
				B	53	28	5.3	1.41	0.57	0.26
258	"	10	4	Q'	56	33	13.0	5.6	2.6	1.37
				B	67	45	20	9.3	5.1	3.2
260	"	11	2	Q'	48	33	10.8	4.6	2.2	1.11
				B	67	46	18.3	8.3	4.1	2.3
287	"		3	Q	54	34	16.3	8.5	4.7	2.8
				B	74	53	29	15.9	9.3	5.3

continued

TABLE 1 cont.

Station	Year	Secchi disk depth	Sea	T	5 m	10 m	20 m	30 m	40 m	50 m
415	1973	13	3	Q"	55	30	12.0	4.8	2.1	1.00
				B	67	45	20	8.9	4.7	2.2
423	"	5	3	Q"	15	3.8	0.25			
				B	10.7	2.1	0.057			
430	"	6.5	1	Q	20	8.0	1.51	0.32		
				B	26	10.7	1.84	0.39	0.097	
435	"	5	2	Q"	18	4.2	0.42			
				B	12.3	2.2	0.084	.00139		
450	"	15	2	Q"	40	20	6.8	2.5	0.94	
				B	47	26	9.8	3.8	1.78	0.82
462	"	15	1	Q"	47	23	6.7	2.6	1.10	0.48
				B	55	33	10.5	4.3	2.1	1.02
484	"	7	2	Q"	24	7.6	1.00			
				B	23	7.1	0.89	0.096		
497	"	5	2	Q"	13	2.3	0.145			
				B	6.8	0.49	(.0105)			

EXPLANATION

Column three: Secchi disk depth in metres.

Column four: State of sea according to ICES Hydro Master Card. 0 = Calm (glassy), 1 = Calm (rippled), 2 = Smooth (wavelets 0.1-0.5 m), 3 = Slight (0.5-1.25 m), 4 = Moderate (1.25 - 2.5 m).

Column five-eleven: T = Transmittance between the surface and the corresponding depth in %, of Q = integrated quanta irradiance from spectral distribution, Q' = according to eq. 1, Q" = according to eqs. 4, B = irradiance at 465 nm.

TABLE 2

Reference	Area	Optical property measured	D·K	T(D) %	Z(10%)/D	Z(1%)/D
POOLE & ATKINS 1929	English Channel	B	1.9±0.3	16±4	1.3±0.2	2.6±0.5
GALL, 1949	English Channel and North Sea	B	1.6±0.1	21±3		
SEGLEM, 1970	Norwegian Sea	B	1.6±0.5	22±11	1.5±0.5	3.2±0.9
This investigation	Norwegian and Barents Seas	B	1.5±0.5	25±10	1.7±0.5	3.3±0.8
CLARKE, 1941	South-western part of the North Atlantic	L	1.9±0.3	15±4	1.4±0.2	2.7±0.3
DIGBY, 1956	Sørgat at Spitsbergen	L	1.4±0.1	26±2	1.9±0.4	
GRAHAM, 1966	Central and Eastern North Pacific Ocean	L	1.7±0.3	18±5		
HOLMES, 1970	Goleta Bay, California	L	1.6±0.4	23±6		3.1±0.7
HØJERSLEV and LUNDGREN, 1977	Icelandic waters	Q	2.3±0.6	12±7	1.1±0.4	2.8±0.9
This investigation	Norwegian and Barents Seas	Q	1.7±0.3	19±6	1.5±0.3	3.3±0.7

EXPLANATION

Column three: The letter B means that T and K are calculated from observations of blue irradiance, L means that the calculations are based on observations of illuminance (in photopic units), Q refers to integrated quanta irradiance.

Column four: K is the vertical attenuation coefficient of B, L or Q between the surface and the Secchi depth.