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THE WAVELENGTH SELECTIVITY
OF LIGHT SCATTERING IN THE
BARENTS SEA

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Abstract

Light scatterance by particles in the Barents Sea decreases about 20% from 406 nm to 630 nm. Phytoplankton does not seem to have any significant influence on this dispersion. Exceptions are extreme situations where one species is dominating the scatterance and is colouring the ocean. It is explained by theoretical means how brown algae can colour the ocean green.

1. INTRODUCTION

In July 1970, August 1972 and May-June 1973 the author made a series of scatterance measurements in the Barents Sea (Fig. 1). The stations and scatterance measurements at 406 nm have been presented in an earlier institute report (AAS 1979a). One of the results was that the volume scattering function for particles, $\beta_p(\theta, \lambda)$, observed at the angle $\theta = 45^\circ$ and the wavelength $\lambda = 406$ nm, had values less than $30 \cdot 10^{-4} \text{ m}^{-1}$ in the cores of the Atlantic waters. While there was a certain resemblance between the iso-lines of temperature, salinity and scatterance below the photic zone, that is below 50-75 m, conditions in the upper layers were rather chaotic, obviously due to primary production.

It is believed that while the particle content of the lower layers consisted mainly of mineral particles and detritus, the upper layers would often be dominated by living phytoplankton stocks. The aim of the present work is to see to which extent the variation in particle types influences the wavelength selectivity of scattering. The question of how brown phytoplankton particles can colour the sea green, is also answered.

2. INSTRUMENTS

The scatterance meter, also called a Tyndall meter, is a laboratory instrument and was constructed by Mr. KJELL NYGÅRD (Institute of Physical Oceanography, University of Copenhagen). The instrument consists of a water sample section between a Hg-lamp and a photo multiplier section. When the collimated light beam from the lamp penetrates the water sample, the amount of scattered light will be a measure of the particle content. The

observations presented in this work were made at 45° angle and at the wavelengths 406, 546, 578 and 630 nm. (The wavelengths referred to are wavelengths in air). A detailed description of the instrument and its calibration has been given earlier by AAS (1979b).

The water sampling bottles used during the cruises were of the Nansen type, manufactured by Bergen Nautic A/S. They were coated internally with epoxy, and although some of the coatings showed signs of beginning corrosion, it has been assumed that this did not influence the particle contents of the samples.

The samples were tapped on glass bottles from Jenaer Glaswerk Schott & Gen., and the bottles were left in a temperate water bath for 30-60 minutes before the measurements, in order to get rid of air bubbles which otherwise would easily form on the inside of the bottles.

3. THE MEASUREMENTS

In 1970 scatterance was only measured at 406 nm, while in 1972 and 73 the wavelengths 546, 578 and 630 nm were also included. The 1972 measurements are the most extensive, and will make the basis for our discussion.

Before the measurement, the sample bottle would be carefully turned upside-down several times in order to get all the particles evenly distributed. Still the reading for each sample would vary about $\pm 20\%$. By estimating the mean value of the signal, it is believed that the error may be $\pm 10\%$.

Values of the volume scattering function β_p due to particles were obtained by subtracting the values for pure water, β_w ,

from the observed values β . The applied values of $\beta_w(45^\circ)$ were 6.3, 1.8, 1.4 and 1.1 in units of 10^{-4} m^{-1} , at the wavelengths 406, 546, 578 and 630 nm respectively, calculated from the results of MOREL (1974).

TABLE 1
MEAN VALUES OF THE VOLUME SCATTERING FUNCTION RELATED TO DEPTH

Depth [m]	N	$\overline{\beta_p}$ [10^{-4} m^{-1}]	β_p (406)	β_p (546)	β_p (578)	β_p (630)
			$\overline{\beta_p}$	$\overline{\beta_p}$	$\overline{\beta_p}$	$\overline{\beta_p}$
0	21	63	1.08	1.06	0.95	0.91
10	"	33	1.08	1.03	0.96	0.94
20	"	41	1.13	0.99	0.96	0.92
30	"	39	1.13	1.02	0.92	0.92
50	"	39	1.09	1.03	0.94	0.94
75	"	35	1.12	1.02	0.93	0.93
100	"	33	1.10	0.99	0.92	1.00
125	"	36	1.09	1.01	0.95	0.95
Closest to bottom	"	45	1.12	1.03	0.94	0.92
All depths	223	39	1.11	1.01	0.94	0.93

Table 1 gives the 1972 observations of $\beta_p(45^\circ, \lambda)$ as a function of depth. At each depth the standard deviation of β_p was of order 20%. The mean value of β_p for all the wavelengths is denoted as $\overline{\beta_p}$ in the table. The actual values of β_p have been normalized relative to this value, in order to see the relative spectral variation.

The table shows that for all depths taken together, the scatterance seems to increase monotonously from the red towards the UV part of the spectrum. The scatterance is about 20% higher at 406 nm than at 630 nm. There is, however, no clear relation between spectral dispersion and depth. So it seems as if the phytoplankton content of the upper layers has no significant influence on the spectral properties.

Another way to examine the observations, might be to group them according to their absolute values. The observations in the red were divided into appropriate size intervals, and the corresponding mean values of violet-blue, green and yellow scatterance were calculated. The result is presented in Fig. 2. Again it is seen that β_p at 578 nm is practically the same as at 630 nm, and that β_p gradually increases towards shorter wavelengths. It is also seen that there does not seem to be any significant change in the spectral dispersion as β_p (630nm) increases. The only exception may be the highest value of β_p (406 nm), which is about 30% higher than the corresponding value of β_p (630 nm), while the difference for all the depths taken together was about 20%, as stated earlier.

The observed dispersion of particles from the Barents Sea is of the same order of magnitude as dispersions observed by other authors, although the details may differ.

KULLENBERG (1969) found that the particle scattering coefficients for the blue and red wavelengths compared well in the Baltic and the Sound, but that scattering of green light was definitely higher. The ratio of green b_p to red b_p varied between 1.1 and 1.3. The observation by HØJERSLEV (1974) from the Baltic, that b_p (655 nm) \approx 0.8 b_p (525 nm), is in agreement with this result.

JERLOV (1974, p. 82) has presented values of b_p (380nm) and b_p (655 nm) from different parts of the world. The ratio between their mean values is ca. 1.06. A much greater dispersion was observed by ZANEVELD and PAK (1973) off the coast of Ecuador. Their ratio β_p (436 nm)/ β_p (546 nm) varies between 1.04 and 1.5, with a probable mean value of 1.25. Their particles then scatter more blue than green light, contrary to the observation by KULLENBERG from the Baltic.

4. THE INFLUENCE OF ALGAE

It is difficult from the 1972-observations presented in the preceding chapter to see any significant influence of phytoplankton on the scattering dispersion. This result may be puzzling, since we would perhaps expect some of the wavelength variation in pigment or chlorophyll absorption to be observed in the scatterance too. In an earlier report (AAS, 1984) we have discussed some of the problems related to the distribution of absorbing matter inside the algae. It was then stated that there is no general relationship between variations in the absorption and scattering by algae, but that the relationship will depend on internal structure, size of the particle and magnitude of refractive and absorption indices. With a multitude of phytoplankton species present, it may be that different maxima and minima of the scatterance are meaned out, so that we obtain the result of Fig. 2.

TABLE 2

THE VOLUME SCATTERING FUNCTION FOR SPECIAL PARTICLE CONTENTS

Water mass	N	$\bar{\beta}_p$ [10^{-4}m^{-1}]	$\frac{\beta_p(406)}{\bar{\beta}_p}$	$\frac{\beta_p(546)}{\bar{\beta}_p}$	$\frac{\beta_p(578)}{\bar{\beta}_p}$	$\frac{\beta_p(630)}{\bar{\beta}_p}$
Clear Atlantic waters	20	26	1.08	1.04	0.99	0.89
St. 423 10-50 m Brown algae	4	88	0.91	1.06	1.07	0.94
St. 430 0 m Brown algae	2	111	1.01	0.84	1.05	1.11
St. 497 0-10 m Brown algae	5	101	0.76	0.96	1.01	1.25

At some of the stations in 1973, however, the scatterance may have been dominated by one species of alga. Table 2 gives the volume scattering function for three stations where the phytoplankton could be observed by the naked eye in the water sample. They all differ significantly from the dispersion of the clear Atlantic waters, which are believed to contain mostly inorganic particles. Especially interesting is Station 430, located just south of Sørkapp at Spitsbergen. The waters here had a very strong, green colour, although the surface waters sampled in a steel bucket looked brown-freckled, due to large aggregates of the brown flagellate Phaeocystis pouchettii. The reason why brown algae can colour the sea green, is that the amount of upward scattered light from the sea depends on the ratio between scattering and absorption coefficients at each wavelength. This is seen clearly from the equation

$$R \approx \frac{1}{1+D_2/D_1} \frac{b_b}{a+b_b} \approx \frac{1}{1+D_2/D_1} \frac{\beta(45^\circ)}{K} \quad 4.1$$

which will be derived in the next chapter. R is the ratio between upward and downward irradiance, D_2 and D_1 are upward and downward distribution functions, b_b is the backscattering coefficient and a the absorption coefficient, β is the volume scattering function and K is the vertical attenuation coefficient of downward irradiance.

The ratio D_2/D_1 will increase from 2 in the blue part of the spectrum to 3 in the red part, as illustrated in Fig. 3. The applied data are theoretical values obtained by TYLER et al. (1972). The vertical attenuation coefficient K has been computed from spectral irradiance distributions presented earlier (AAS and BERGE, 1976). The result is given in Fig. 3 together with the observed values of the scattering function β . Maximum scatterance lies clearly in the red part of the spectrum, which accounts for the brown colour of the algae.

The irradiance reflectance R can now be calculated by means of eq. 4.1. As is seen in Fig. 3, almost all of the red light has been absorbed. The remaining light lies in the blue-green-yellow part of the spectrum, and the sea will consequently appear green.

5. A TWO-STREAM IRRADIANCE MODEL

The classical equation of transfer may be written

$$\frac{dL}{dz} \cos \theta = -cL + L_* \quad 5.1$$

where z is the vertical coordinate, positive downwards, and

$L = L(z, \theta, \phi)$ is the radiance at the depth z from the direction θ, ϕ . θ is the zenith distance and ϕ the azimuth angle. c is the attenuation coefficient, and L_* is the source function (CHANDRASEKHAR, 1960) or path function (JERLOV, 1976), defined by

$$L_*(z, \theta, \phi) = \int_{4\pi} \beta(\theta, \phi, \theta', \phi') L(z, \theta', \phi') d\Omega' \quad 5.2$$

$d\Omega'$ is an infinitesimal solid angle in the direction θ', ϕ' . $\beta(\theta, \phi, \theta', \phi')$ is the scattering function for light scattered with direction θ, ϕ from the direction θ', ϕ' .

We let $d\Omega$ denote a solid angle in the direction θ, ϕ . If we integrate eq. 5.1 for all directions, we obtain

$$\begin{aligned} & \frac{d}{dz} \int_{4\pi} L(z, \theta, \phi) \cos \theta \, d\Omega \\ &= \frac{d}{dz} \left[\int_{2\pi_1} L \cos \theta \, d\Omega - \int_{2\pi_2} L |\cos \theta| \, d\Omega \right] \\ &= \frac{d}{dz} [E_1 - E_2] \\ &= -c \int_{4\pi} L d\Omega + \int_{4\pi} L_* d\Omega \\ &= -c E_0 + \int_{4\pi} d\Omega \int_{4\pi} L(z, \theta', \phi') \beta(\theta, \phi, \theta', \phi') d\Omega' \quad 5.3 \end{aligned}$$

Here the index 1 denotes downward and 2 upwards, so that $2\pi_1$ means the hemisphere of downward flux, that is the upper hemisphere. E_1 and E_2 mean the downward and upward irradiances respectively.

By changing the sequence of integrations in the last double integral, we find that it simply becomes bE_0 , where b is the scattering coefficient and E_0 is the scalar irradiance. Eq. 5.3 can now, since

$$c = a + b \quad 5.4$$

where a is the absorption coefficient, be written

$$\frac{d}{dz}(E_1 - E_2) = -cE_0 + bE_0 = -aE_0 = -a(E_{01} + E_{02}) \quad 5.5$$

where E_{01} and E_{02} are the downward and upward scalar irradiances. This is the classical GERSHUN equation for a vertically stratified medium (GERSHUN, 1939).

Our next step will be to limit the integration of eq. 5.1 to the upper hemisphere. We obtain

$$\begin{aligned} \frac{d}{dz} \int_{2\pi_1} L \cos \theta \, d\Omega &= \frac{d}{dz} E_1 \\ &= -c \int_{2\pi_1} L \, d\Omega + \int_{2\pi_1} L_* \, d\Omega \\ &= -cE_{01} + \int_{2\pi_1} \left(\int_{2\pi_1} \beta(\theta, \phi, \theta', \phi') \, d\Omega \right) L(z, \theta', \phi') \, d\Omega' \\ &+ \int_{2\pi_2} \left(\int_{2\pi_1} \beta(\theta, \phi, \theta', \phi') \, d\Omega \right) L(z, \theta', \phi') \, d\Omega' \end{aligned} \quad 5.6$$

The last two integrals will depend on the angular radiance distribution. But since we have that

$$\int_{2\pi_1} \beta(\theta, \phi, 0, \phi') \, d\Omega = b_f \quad 5.7$$

$$\int_{2\pi_1} \beta(\theta, \phi, \frac{\pi}{2}, \phi') \, d\Omega = \frac{b}{2} \quad 5.8$$

$$\int_{2\pi_1} \beta(\theta, \phi, \pi, \phi') \, d\Omega = b_b \quad 5.9$$

where b_f and b_b are the forward and backward scattering coefficients respectively, and since the integral will vary monotonously between these values for varying θ' , we know that

$$\frac{b}{2} E_{01} < \int_{2\pi_1} \left(\int_{2\pi_1} \beta(\theta, \phi, \theta', \phi') \, d\Omega \right) L(z, \theta', \phi') \, d\Omega' < b_f E_{01} \quad 5.10$$

$$b_b E_{O2} < \int_{2\pi_2} \left(\int_{2\pi_1} \beta(\theta, \phi, \theta', \phi') d\Omega \right) L(z, \theta', \phi') d\Omega' < \frac{b}{2} E_{O2} \quad 5.11$$

We may then substitute the first integral on the right side of eq. 5.6 with $x_1 b_f E_{O1}$, where x_1 is a number equal to or less than 1, and substitute the last integral of 5.6 with $x_2 b E_{O2}$, where x_2 is a number equal to or less than 0.5. Eq. 5.6 can now be written

$$\frac{dE_1}{dz} = -cE_{O1} + x_1 b_f E_{O1} + x_2 b E_{O2} \quad 5.12$$

where

$$x_1 = \frac{1}{b_f E_{O1}} \int_{2\pi_2} \left(\int_{2\pi_1} \beta(\theta, \phi, \theta', \phi') d\Omega \right) L(z, \theta', \phi') d\Omega' \quad 5.13$$

$$x_2 = \frac{1}{b E_{O2}} \int_{2\pi_2} \left(\int_{2\pi_1} \beta(\theta, \phi, \theta', \phi') d\Omega \right) L(z, \theta', \phi') d\Omega' \quad 5.14$$

If we subtract eq. 5.12 from eq. 5.5, we find that

$$\frac{dE_2}{dz} = (a+x_2 b) E_{O2} - (b-x_1 b_f) E_{O1} \quad 5.15$$

By introducing the downward and upward distribution functions D_1 and D_2 (TYLER and PREISENDORFER, 1962), defined as

$$D_1 = E_{O1}/E_1 \quad 5.16$$

$$D_2 = E_{O2}/E_2 \quad 5.17$$

and by writing

$$a_1 = aD_1 \quad 5.18$$

$$b_1 = (b_b + (1-x_1)b_f)D_1 \quad 5.19$$

$$c_1 = (c-x_1 b_f)D_1 = (a+b_b + (1-x_1)b_f)D_1 = a_1 + b_1 \quad 5.20$$

$$a_2 = aD_2 \quad 5.21$$

$$b_2 = x_2 b D_2 \quad 5.22$$

$$c_2 = (a+x_2 b)D_2 = a_2 + b_2 \quad 5.23$$

the equations 5.12 and 5.15 obtain the forms

$$\frac{dE_1}{dz} = -c_1 E_1 + b_2 E_2 \quad 5.24$$

$$-\frac{dE_2}{dz} = -c_2 E_2 + b_1 E_1 \quad 5.25$$

These are two-stream equations, provided b_1, b_2, c_1 and c_2 can be regarded as constants. The same equations were obtained in a different way by KOZLYANINOV and PELEVIN (1966), but the coefficients b_1, b_2, c_1 and c_2 there had less precise definitions.

It should be noted that so far the equations 5.24 and 25 are exact. In order to proceed, however, we have to make some approximations. The first will be that since the variation of E_1 and E_2 along the z axis is likely to be much greater than the variation of x_1, x_2, D_1 and D_2 , we can for a layer of the ocean with constant a and b regard b_1, b_2, c_1 and c_2 as constants too.

Elimination of E_2 in eq. 5.24 by means of eq. 5.25 now gives

$$\frac{d^2 E_1}{dz^2} = (c_2 - c_1) \frac{dE_1}{dz} + (c_1 c_2 - b_1 b_2) E_1 \quad 5.26$$

If we assume that E_1 has the form

$$E_1(z) = E_1(0) e^{-Kz} \quad 5.27$$

where K is the vertical attenuation coefficient of irradiance, eq. 5.26 gives that

$$K = \left[\left(\frac{c_1 + c_2}{2} \right)^2 - b_1 b_2 \right]^{\frac{1}{2}} - \frac{c_2 - c_1}{2} \quad 5.28$$

From eq. 5.24 we see that if E_1 has the form given by 5.27, E_2 must necessarily have the same form:

$$E_2(z) = E_2(0)e^{-Kz}. \quad 5.29$$

Substitution of E_1 and E_2 from eqs. 5.27 and 5.29 in eq. 5.26 gives that

$$R = \frac{E_2(z)}{E_1(z)} = \frac{E_2(0)}{E_1(0)} = \frac{c_1 - K}{b_2} \quad 5.30$$

R is the irradiance reflectance or irradiance ratio. It may be regarded as the albedo of the ocean beneath the surface.

If we return to eq. 5.28, we see that K may be written

$$K = \frac{c_1 + c_2}{2} \left[1 - \frac{4b_1 b_2}{(c_1 + c_2)^2} \right]^{1/2} - \frac{c_2 - c_1}{2} \quad 5.31$$

For natural ocean waters a will be of the same order of magnitude as b (JERLOV, 1976, table XV and XIII). D_1 and D_2 will also be of the same order (TYLER and PREISENDORFER, 1962, TYLER et al., 1972). Since $L(z, \phi', \phi')$ in eq. 5.13 will have its greatest values close to zenith, x_1 is likely to be close to 1. Still the factor $(1-x_1)b_f$ in eq. 5.19 is not necessarily much smaller than the factor b_b , because b_b itself is much smaller than b_f . We will write

$$\frac{b_1}{D_1} = b - x_1 b_f = b_b + (1-x_1)b_f = y_1 b_b \quad 5.32$$

where y_1 is a number greater than or equal to 1. It is clear, however, that b_1 will be much smaller than a_1 and c_1 .

The upward radiance in eq. 5.14 will have its greatest values in the horizontal direction, and x_2 will be somewhat smaller than 0.5. How much smaller can not be said without a more thorough investigation. The important fact for us is that

b_2 will be smaller than c_2 , and that the term $4b_1b_2/(c_1+c_2)^2$ will be a number much smaller than 1.

The square root in eq. 5.31 can then be expanded in series, and K becomes

$$\begin{aligned}
 K &\approx \frac{c_1+c_2}{2} \left[1 - \frac{1}{2} \frac{4b_1b_2}{(c_1+c_2)^2} - \frac{1}{8} \frac{(4b_1b_2)^2}{(c_1+c_2)^4} - \dots \right] - \frac{c_2-c_1}{2} \\
 &= c_1 - \frac{b_1b_2}{c_1+c_2} - \frac{b_1^2b_2^2}{(c_1+c_2)^3} - \dots
 \end{aligned}
 \tag{5.33}$$

We see that to a first approximation

$$K \approx c_1 \tag{5.34}$$

With this value eq. 5.30 gives that

$$R \approx 0 \tag{5.35}$$

that is, the irradiance reflectance is zero to a first approximation. If we include that other terms in the expansion for K , we obtain

$$\begin{aligned}
 R &= \frac{b_1}{c_1+c_2} \left[1 + \frac{b_1b_2}{(c_1+c_2)^2} + \dots \right] \approx \frac{b_1}{c_1+c_2} \\
 &= \frac{b_1}{a_1+b_1+a_2+b_2} = \frac{b_1}{a_1+b_1} \frac{1}{1 + \frac{a_2+b_2}{a_1+b_1}} \\
 &= \frac{b_b}{a+y_1b_b} \frac{y_1}{1 + \frac{(a+x_2b)D_2}{(a+y_1b_b)D_1}}
 \end{aligned}
 \tag{5.36}$$

Now we shall assume that $x_1 = 1$, so that $y_1 = 1$, and that y_1b_b and x_2b are so much smaller than a that they can be neglected in the denominator of the last term above. We then have that

$$R \approx \frac{b_b}{a+b_b} \frac{1}{1 + \frac{D_2}{D_1}} \quad 5.37$$

For blue light D_2/D_1 can be approximately 2.1 (TYLER and PREISENDORFER, 1962, table XIV), and with this value eq. 5.37 gives

$$R \approx \frac{1}{3} \frac{b_b}{a+b_b} \quad 5.38$$

KOZLYANINOV and PELEVIN, who started with the same equations (5.24 and 25), made some approximations which correspond to $x_1 = 1$, $x_2 b = b_b$ and $D_2 = D_1$. They then obtained the factor 1/2 rather than 1/3 in eq. 5.38.

In real life x_1 is likely to be less than 1, so that y_1 becomes greater than 1, and $x_2 b$ may be comparable with a . Both the numerator and the denominator of the last term in eq. 5.36 will then be greater than the values we just assigned to them, but the ratio may still have a value about 1/3.

From data by HØJERSLEV from the Mediterranean and the Baltic (1973, 1974) it has been found (AAS, 1976) that for blue light

$$R \approx 0.00725 \frac{b}{a+0.145b} \quad 5.39$$

This expression corresponds fairly well with eq. 5.38, provided $b_b = 0.022b$. Since JERLOV gives that $b_b = 0.02b$ for ocean surface water (1976, table IX), eq. 5.38 may give a reasonable estimate of the irradiance reflection. Further support for this expression comes from other authors which have obtained it by different methods.

GORDON et al. (1975) applied a Monte Carlo technique and found that for small optical depths, and with only direct

sunlight,

$$R = 0.0001 + 0.3244 \frac{b_b}{a+b_b} + 0.1425 \frac{b_b^2}{(a+b_b)^2} + \dots \quad 5.40$$

With only skylight present, the expression became

$$R = 0.0003 + 0.3687 \frac{b_b}{a+b_b} + 0.1802 \frac{b_b^2}{(a+b_b)^2} + \dots \quad 5.41$$

For most practical purposes these expressions can be regarded as identical with eq. 5.38.

MOREL and PRIEUR (1977) obtained by a successive order scattering method the expression

$$R = 0.33 b_b/a \quad 5.42$$

which also is close to eq. 5.38.

WHITLOCK et al. (1981) compared observed R with eq. 5.38 for very turbid river waters (c varied between 8 and 30 m^{-1} , b/a between 3 and 10 and b_b/a between 0.05 and 0.5). They found very poor agreement, which is not surprising, since most of the assumptions made in order to arrive at eq. 5.38, were not valid in their case. b_b/a was not always much smaller than one, and b_2 might be much greater than a_2 .

We shall now make the approximation that eq. 5.37 can be used at all visible wavelengths. Eq. 5.34 gave that to a first approximation

$$K \approx c_1 = a_1 + b_1 = (a + y_1 b_b) D_1 \quad 5.43$$

Setting $y_1 = 1$ and substituting for $a + b_b$ in eq. 5.37, we find that

$$R \approx \frac{1}{1 + D_2/D_1} \frac{b_b \cdot D_1}{K} \quad 5.44$$

If we further assume that $\beta(45^\circ) \approx 0.033b$ (JERLOV, 1976, table X), $b_b \approx 0.022b$ and that $D_1 \approx 1.5$ due to low sun and moderately turbid ocean water, like at Station 430 in the preceding chapter, the irradiance reflectance can be written

$$R \approx \frac{1}{1+D_2/D_1} \frac{\beta(45^\circ)}{K} \quad 5.45$$

Another interesting result is that eqs. 5.37 and 43 give

$$a = \frac{K}{D_1} \left[1 - R \left(1 + \frac{D_2}{D_1} \right) \right] \quad 5.46$$

$$b_b = \frac{K}{D_1} R \left(1 + \frac{D_2}{D_1} \right) \quad 5.47$$

This means that a and b_b can be found from measurements of downward and upward irradiance, provided we are able to estimate D_1 and the ratio D_2/D_1 . A crude estimate of D_1 is $\sec j$, where j is the angle of the refracted sunrays, and D_2/D_1 is probably similar to the function in Fig. 3.

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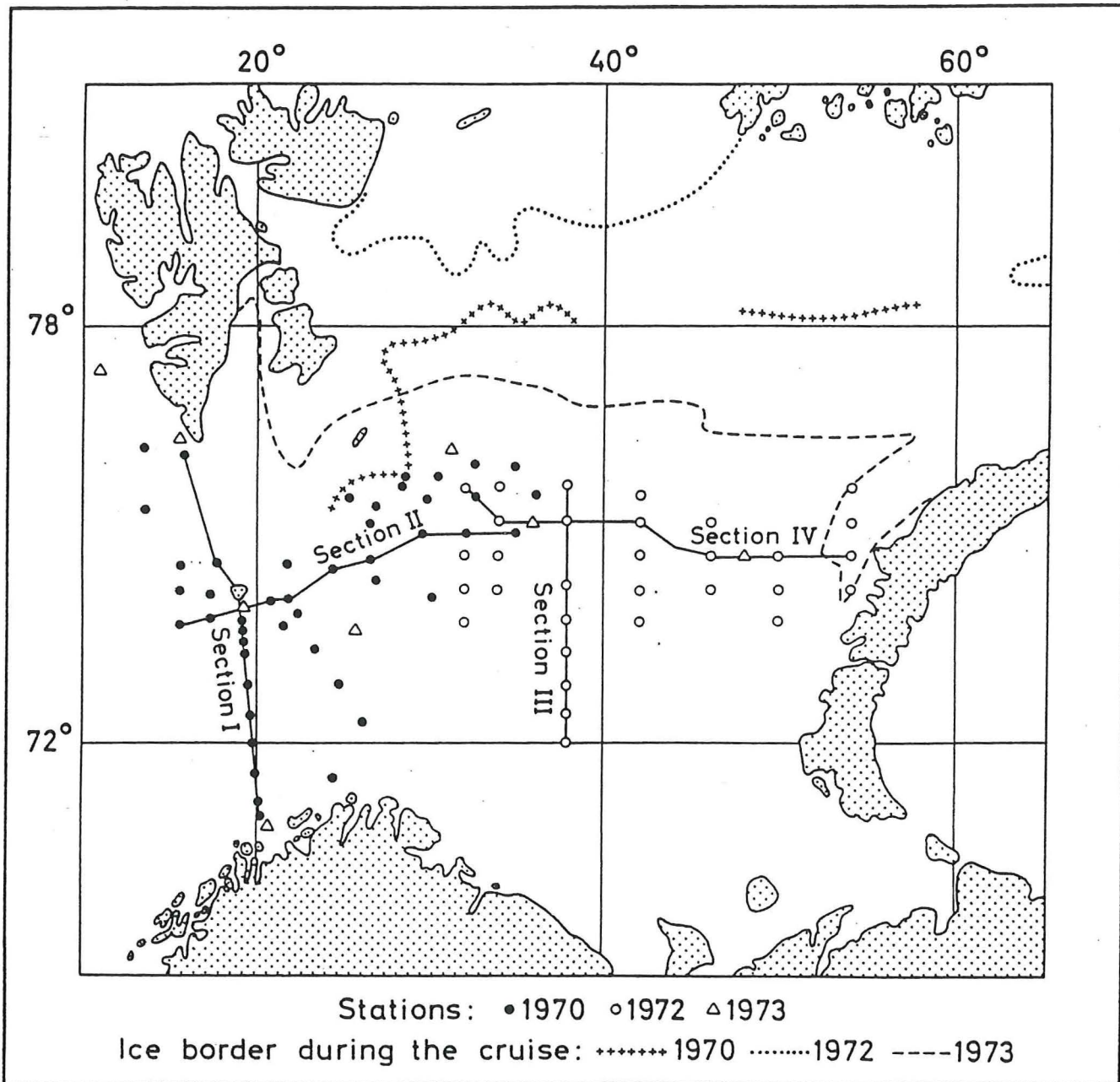


Fig.1. Location of stations with scatterance measurements.

Fig 2. The particle scatterance of violet-blue, green and yellow light as a function of the red scatterance.

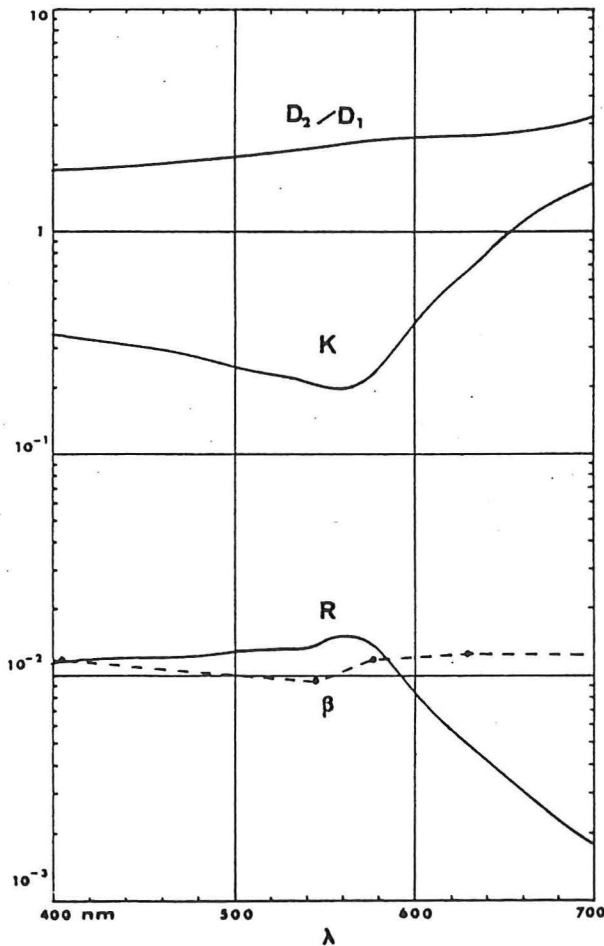
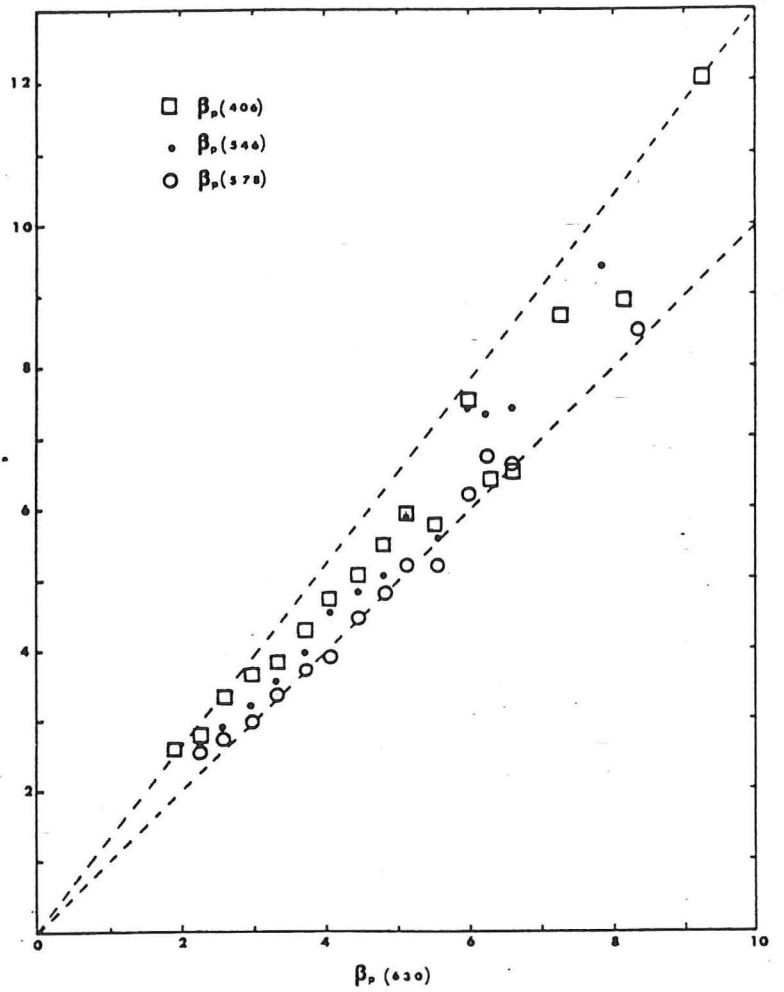


Fig.3. Optical properties at Station 430. D_2/D_1 is the ratio between the upward and downward distribution functions. K is the vertical attenuation coefficient of downward irradiance, and R is the irradiance reflectance. β is the scattering function at 45° . K and β are in units of m^{-1} , while D_2/D_1 and R are non-dimensional.