A study of the Baltic water optical transparency*

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Light attenuation coefficient
Optical properties
Baltic water

JERZY DERA, SŁAWOMIR SAGAN
Institute of Oceanology,
Polisch Academy of Sciences,
Sopot

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Abstract

The light beam attenuation coefficient variability in time and space in the visible band of light spectrum in the Southern Baltic are presented. This coefficient was changing from about 0.3 m^{-1} to 4.5 m^{-1} for the wavelength 425 nm. The results of *in situ* measurements collected during the international PEX 86 experiment as well as the results of measurements performed by the authors during several cruises in 1986–1988 were used to prepare a set of optical characteristics of the examined region. Some earlier data, found in the literature, were also taken into account. Basing on the theoretical formulae and on some other empirical investigations the contribution of absorption and scattering in the light attenuation process, were estimated for the selected wavelengths. The possibility of estimation of the underwater visibility conditions on the basis of attenuation coefficient data is also presented.

1. Introduction

The transparency of water, which is usually described by a light beam attenuation coefficient, is a basic inherent optical property of the sea. On the one hand, it determined the radiant energy transfer in the water body; on the other hand, it is, in the ultraviolet and visible band of the light spectrum, a sensitive indicator of the suspended particles and organic substances in the sea.

The first, available in literature, descriptions of variability of the water transparency in the Baltic Sea and causes of this variability can be found in works by Joseph (1955) and Jerlov (1955). The fast development of photoelectronics and its application to hydrooptics in the 1960s was essential for further progress in optical investigations of various seas, and among those, the Baltic (Jerlov, 1965; Ivanov *et al*, 1966). This development was expanded by introduction of a new operational definition of optical properties of sea water (Preisendorfer, 1961) and also by the fact that the role of organic yellow substance (Jerlov, 1953; Kalle, 1961, 1966) and suspended particles (van de Hulst, 1957; Kullenberg, 1974) in the process of light attenuation in the sea was investigated and described. The investigations clearly showed that the optical properties of the Baltic Sea water are quite different from those properties of pure sea water and also of common

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oceanic waters. The explanation of this difference lies in the fact that the content of organic substances (Pempkowiak, 1977, 1989) and the content of suspended particles of solids of different types (Jemelyanov, Pustelnikov, 1976; Jemelyanov, Stryuk, 1981; Jonasz, 1983) are quite high in the Baltic. A mixture of organic substances in the water absorbs a short-wave band of the light spectrum. The absorption varies with wavelengths, being low in the red light band and increasing significantly towards short waves, especially towards the violet and ultraviolet light waves (Dera, 1967; Kopelevich *et al*, 1974). Suspended particles in the Baltic water strongly attenuate the light of all wavelengths in the visible and ultraviolet region of radiation (Pustelnikov, Shmatko, 1971; Dera *et al*, 1978). This attenuation results partly from absorption of the light by organic particles, including phytoplankton, but mainly from its scattering on particles which are large compared with the length of light waves being scattered (Kullenberg, 1969). The characteristics of such scattering are, among others, described by Burt (1956), Shifrin and Salganik (1973). Light attenuation caused by the factors mentioned above is incomparable with light attenuation caused by salt ions and it can be stated that the latter one is negligible. The light attenuation caused by water molecules becomes essential when the wavelengths are longer than about 600 nm, as these are strongly absorbed by water (Ivanoff, 1972; Hojerslev, 1974; Kopelevich *et al*, 1974; Dera *et al*, 1978).

As follows from the above considerations and from other papers, the nature of light attenuation in the Baltic water is generally known. However, the regional as well as seasonal characteristics and trends in variability of this process have not been examined. There are only scarce data concerning the spatial distribution of light attenuation coefficient and these data were collected in single cruises to the Baltic Sea (Dera, 1965; Hojerslev, 1974; Krężel, Sagan, 1986; Nikolaev, 1987). There are available only random data on the spectral distribution of this coefficient (Pustelnikov, Shmatko, 1971; Gohs *et al*, 1978; Dera *et al*, 1978; Lundgren, 1976). There exist only fragmentary data from some regions and single cruises which describe a quantitative influence of organic substances and suspended particles on the light attenuation in the Baltic Sea (Dera *et al*, 1978; Gohs *et al*, 1978; Jonasz, Prandtke, 1986).

The essential, from the optics point of view, components of sea water such as; suspended particles, organic substances and also pigments, occur in the Baltic Sea in concentrations which are highly variable in space and in time. It results from many phenomena, such as: discharges of polluted fresh waters and other wastes from land, rise of the mud and sand from the shore and sea bottom during storms, primary production and some other biological processes, precipitation of aerosol from the polluted atmosphere, and some others, not fully identified. A random character of changes of sources of the mentioned above components, which are optically important in the Baltic waters, does not allow to make a quantitative characterization of the water transparency in the Baltic and thus statistical investigations and searching for a correlation between optical properties of those components and others, better known properties, are essential.

Such investigations have been carried out by the authors and co-workers since 1986 and they have been introduced to the part of the Baltic Monitoring Program which was conducted on r/v "Oceania". Participation in the international experiment PEX 86 (Dybern and Hansen, 1989) and in some other expeditons to the Baltic Sea in 1986–1988 allowed the authors to collect a new data. This big set of data, together with the data presented in the literature, enabled the authors to show the dynamics of transparency variability of the Baltic waters and to characterize this variability up to the present state of knowledge. Characterization of the variability of transparency was the main aim of this paper, though it is not, so far, a statistical characteristic which on the other hand requires the long-term and systematic measurements made in the entire region of the Baltic Sea.

2. Definitions and optical relations

An operational definition of the light beam attenuation coefficient arises from the radiant energy transfer equation (Preisendorfer, 1961). In a case of stationary conditions and a constant refraction coefficient, n = const., this equation can be written as follows:

$$\frac{\mathrm{d}L(r)}{\mathrm{d}r} = -cL(r) + L_*(r) + L_\eta(r), \tag{1}$$

where:

$L(r)$ – the radiance function of light in the direction of propagation along a path r, measured in [$\mathrm{W/m^2 sr}$],

$L_*(r)$ – the path function measured in [$\mathrm{W/m^3 sr}$],

$L_\eta(r)$ – the source function measured in [$\mathrm{W/m^3 sr}$],

c – the light beam attenuation coefficient measured in [$\mathrm{m^{-1}}$].

This integral-differential equation (the path function L_* described by an integral; Preisendorfer, 1961) can be fully applied to the marine environment where the strong sources of scattered light radiation (L_*) and some other sources of light radiation (L_η), *ie* bioluminescence (Dera, Węglańska, 1980), are present. As a general form of analytical solution of the above equation is not known, the light beam attenuation coefficient c existing in this equation can be evaluated only after certain simplification of conditions governing the application of equation (1) to measurements of this coefficient. In order to achieve this, the transmittance of light beam – which is described with a radiance function L – is measured along a path r, and additionally it is assumed that $L_\eta = 0$, therefore it is assumed that there are no biological or other sources of light. A proper construction of a measuring device with application of a thin parallel beam of artificial light (Jerlov, 1976; Hojerslev, Larsen, 1980) provides such conditions of $\frac{\mathrm{d}L}{\mathrm{d}r}$ measurements in which the path function $L_*(r) \ll L(r)$, and thus it can be neglected. On fulfilment of such conditions, equation (1) leads directly to the operational definition of the light beam attenuation coefficient c:

$$\frac{\mathrm{d}L(r)}{\mathrm{d}r} = -cL \tag{2}$$

or upon integration over the path r in the investigated medium:

$$\frac{L_r}{L_0} = \mathrm{e}^{-cr}. \tag{3}$$

The radiance ratio L_r/L_0 of transmitted light beam along the defined path r is called transmittance of the light beam along this path and a transmittance along a path of 1 m in the marine environment is called, in the physical but not only in common sense, water transparency. Unfortunately, these measurements are not straightforward and they create some errors which were described by Afonin and Spiridonov (1977), Kozlyaninov (1981), Haaron *et al* (1983) and others. One should also remember that the transparency of sea water, thus in consequence the light beam attenuation coefficient, is a complicated function of light wavelength $c(\lambda)$ and must be evaluated for defined wavelengths λ.

It is commonly assumed that the additivity of absorption and scattering are the processes contributing to light attenuation. Thus, the light beam attenuation coefficient $c(\lambda)$ is a sum of absorption coefficient $a(\lambda)$ and scattering coefficient $b(\lambda)$:

$$c(\lambda) = a(\lambda) + b(\lambda). \tag{4}$$

Furthermore, it is known that in varying bands of spectrum different components of sea water have a dominant influence on the light beam attenuation. For example, in the infrared band the influence of strong absorption of radiation by H_2O molecules in liquid water decidedly dominates. In the violet band, the light beam attenuation in pure oceanic water samples arises from strong molecular scattering while in eutrophic waters—from the light absorption by organic yellow substance, phytoplankton, and organic detritus (Ivanoff, 1972; Kopelevich *et al*, 1974; Jerlov, 1976; Dera, 1983). The light attenuation in the green band of light spectrum is usually caused by light scattering on suspended solid particles. It is convenient to extend the assumption concerning the additivity of light absorption and scattering in the sea water and to assume that absorption and scattering are caused by particular groups of components of sea water:

$$c(\lambda) = c_w(\lambda) + a_y(\lambda) + b_p(\lambda) + a_p(\lambda) + c_0(\lambda), \tag{5}$$

where:

$c_w(\lambda) = a_w(\lambda) + b_w(\lambda)$ — light beam attenuation coefficient, for a particular wavelength and for clear water, which equals to a sum of light absorption coefficient caused by water and coefficient of molecular scattering by water molecules,

$a_y(\lambda)$ — absorption coefficient by organic yellow substance present in water,

$b_p(\lambda)$ — scattering coefficient on solid suspended particles,

$a_p(\lambda)$ — absorption coefficient by chlorophyll and other pigments present in marine plankton cells and also by some other particles suspended in water. The sum $a_p + b_p = c_p$ is attenuation coefficient caused by particles suspended in water,

$c_0(\lambda)$ — light beam attenuation coefficient caused by other substances which "artificially" contaminate water (*ie* hydrocarbons).

Equation (5) simplifies interpretation of the results of spectral measurements of light beam attenuation coefficient $c(\lambda)$ in various marine regions. In this equation the attenuation caused by salt ions present in sea water is disregarded, being negligibly low (Jerlov, 1976).

Basing on what is known about a spectral distribution of patricular coefficients from formula (5) and considering comparisons of measured, in the sea, values $c(\lambda)$ for different wavelengths λ, a conclusion concerning the content of different components in the investigated water can be drawn. For example, if in the green band of light spectrum (500 – 550 nm) $c \gg a_w$, it means that this water, most probably, contains high concentrations of suspended particles; if $c_{violet} \gg c_{red}$, it implies that water contains large quantities of dissolved organic matter, and the like. For the marine conditions and for the infrared ($\lambda > 1$ µm) it can be generally assumed that $c(\lambda) \approx c_w(\lambda) \approx a_w(\lambda)$ and this arises from the above mentioned very strong absorption of infrared radiation by water; this strong absorption causes that the influence of other components of sea water on the light beam attenuation is negligible.

The dependence between the listed coefficients of light absorption, scattering, and attenuation in the sea and relations between these coefficients and some other optical properties of the sea arise from the theory of radiant energy transfer and from the empirical data (Preisendorfer, 1961; Jerlov, 1976; Morel, Smith, 1982; Dera, 1983). Jerlov gives a relation between the absorption coefficient of ultraviolet light (380 nm) caused by yellow substance a_y and the total coefficient of light attenuation caused by all the substances contained in water (with an exclusion of water itself, $c-c_w$) and this is given for two bands of spectrum;

$$(c-c_w)_{380\,nm} - C(c-c_w)_{655\,nm} = (a_y)_{380\,nm} \tag{6}$$

where C is an equation parameter which depends on composition and concentration of suspended particles in water; for a particular water mass it has a constant value.

Jerlov also suggests making use of the ratio $(c-c_w)_{380}/(c-c_w)_{655}$ as an indicator of selectivity of attenuation in relation to the wavelength; it results from the influence of yellow substance and suspended particles. This ratio, in the case of oceanic waters, is approximately constant and equal to 1.8, while in the case of the Baltic Sea (and some other waters containing yellow substance and suspended particles in high concentrations) it is considerably different (see section 4). In the infrared (600 – 750 nm) band of light spectrum, chlorophyll "a" is practically the only, besides the water itself, absorbent of the light in sea water. Thus, it can be roughly assumed that:

$$(c-c_w)_{\lambda_2} - (c-c_w)_{\lambda_1} \approx a_{chl.\lambda_2}, \tag{7}$$

where $500 < \lambda_1 < 550$, $600 < \lambda_2 < 750$. Other relations between the optical properties of sea water are presented by Ivanoff *et al* (1961). Many relations which had been empirically established and which concern the Gulf of Gdańsk were presented by Dera *et al* (1978). Among the relations between the light attenuation coefficient c and the remaining optical functions there is one which is essential and it is a connection of the coefficient c with the attenuation of downward irradiance in the sea and also with the underwater visibility.

Usually, the values of diffuse attenuation function of downward irradiance in the sea $K_{\downarrow}(\lambda)$ (Jerlov, 1976) are larger than the values of absorption coefficient $a(\lambda)$ and smaller than the values of attenuation $c(\lambda)$:

$$a(\lambda) < K_{\downarrow}(\lambda) < c(\lambda). \tag{8}$$

The relation between these functions depends however on directional distribution of the radiance in the underwater light field which exists at a certain environmental situation. If the upward irradiances—which in the case of the Baltic Sea have values barely reaching 1% of the downward irradiance $E_{\downarrow}(\lambda)$—are disregarded, then basing on the Gerschun's (1959) formula the $K_{\downarrow}$ function, which depends on the absorption coefficient, can be calculated:

$$K_{\downarrow}(\lambda) \approx a(\lambda)\frac{E_{0\downarrow}(\lambda)}{E_{\downarrow}(\lambda)} \approx a(\lambda)D_{\downarrow}(\lambda). \tag{9}$$

The ratio of the downward scalar irradiance $E_{0\downarrow}(\lambda)$ to the downward vector irradiance $E_{\downarrow}(\lambda)$, which is called the downward flux distribution function $D_{\downarrow}(\lambda)$, is a inverse of mean cosine of an angle θ. The angle θ is a deviation of the mean radiant flux from the upper hemisphere, from the zenith (Morel, Smith, 1982). In the case of the Baltic Sea, as follows from numerous measurements (Woźniak, Hapter, 1985), the averaging value of the downward flux distribution function in the visible band equals:

$$D_{\downarrow} \equiv \frac{1}{\cos\theta_{\downarrow}} \equiv \frac{1}{\bar{\mu}_{\downarrow}} \approx 1.27 \pm 0.08. \tag{10}$$

Relatively simple measurements of attenuation of the downward irradiance in the Baltic Sea, which lead to determination of $K_{\downarrow}(\lambda)$ function, allow on the basis of approximate function (9) to estimate the coefficient of light absorption $a(\lambda)$. An error in this estimation may reach 10% and it results mainly from the statistical scatter of the function $D_{\downarrow}$ values which is calculated according to formula (10). At the same time, the measured values of light beam attenuation coefficient $c(\lambda)$ allow to determine the scattering coefficient $b(\lambda)$ on the basis of formula (4). In such an indirect way, the approximate information about contribution of absorption and scattering in the process of light attenuation in the investigated waters can be roughly obtained.

A parameter $\bar{\omega}$ which is ratio of two coefficients

$$b(\lambda)/c(\lambda) = \bar{\omega}\ (\lambda) \tag{11}$$

provides a direct information about contribution of scattering in the process of light attenuation and it is called a probability of photon survival or a single scattering albedo (Morel, Smith, 1982).

Some authors (Smith, Baker, 1978; Pelevin, Rutkovskaya, 1979; Woźniak, 1989) basing on a great number of data obtained from the measurements of function $K_{\downarrow}(\lambda)$ and basing on some other environmental properties *ie* concentration of chlorophyll "a", proposed a new and more exact, compared to what had been initiated by Jerlov (1964), methods of optical classification of sea water. Namely, correlation between the attenuation function of irradiance $K_{\downarrow}(\lambda)$ and another selected property of natural water which was assumed as an index of water type, was found. Woźniak (1989) determined, for the investigated water, the following empirical regression equation which describes the statistical correlation between function $K_{\downarrow}(\lambda)$ $[m^{-1}]$ and the chlorophyll "a" concentration B [mg/m^3]:

$$K_{\downarrow}(\lambda) = K_{\downarrow w}(\lambda) + B[C(\lambda)\, e^{-\alpha(\lambda)B} + k(\lambda)], \tag{12}$$

where the following parameters of the above equation are statistically determined and constant, for a particular wavelength: $K_w(\lambda)$, $C(\lambda)$, $\alpha(\lambda)$, $k(\lambda)$. The parameter B, being a hypothetical chlorophyll "a" concentration in water, is here an index of natural water classification (see section 7). Thus, the determination of a spectrum of function $K_{\downarrow}(\lambda)$ can be obtained from equation (12) and this function, together with the relations given above, can be used for the estimation of some other optical characteristics of sea waters.

The underwater visibility can be, to some approximation, determined by means of the light beam attenuation coefficient. According to Duntley (1963) a big, dark objects present in the deep sea can be seen in the horizontal direction from a maximum distance:

$$r_{max} \approx d/c, \tag{13}$$

where the parameter d equals to about 4. More precisely, the parameter d depends on the eye threshold sensitivity to contrast: $d = \ln(C_0/C_{rp})$. The real inherent contrast of an object C_0 in a case of an ideal black body equals to -1, while the average threshold sensitivity of eye, and thus the minimal apparent contrast C_{rp} observable by human eye (positive when the object is lighter than the background or negative when the object is darker than the background) amounts to about 0.02 (Briggs, Hatchett, 1965; Olszewski, 1973). The light beam attenuation coefficient c in formula (13) is usually referred to the light wavelengths in the range of maximum transmittance in particular water. At the same time, as it arises from the radiation transfer theory, the transmittance of an object contrast C_r/C_0 towards the horizontal direction and along a path r decreases exponentially with the distance r in the homogeneous deep sea. It can be represented as follows:

$$C_r = C_0 e^{-cr}. \tag{14}$$

From this equation a straightforward dependence between the apparent contrast C_r and the light beam attenuation c can be seen. In the case of observation of an object in any direction, but not only towards the horizontal direction, formuale (13) and (14) have a different form as there appears a term which includes the dependence on the direction of the observation and the attenuation coefficient of radiance (Duntley, 1963; Preisendorfer, 1964).

3. Materials and methods

The new results of light beam attenuation coefficient measurements which are used in this paper were collected in the Baltic in 1986–1988. These results were obtained during research cruises of r/v "Oceania" organized by the Institute of Oceanology (Polish Academy of Sciences, Sopot). The region of investigations as well as station distribution are shown in Figure 1. The dates of measurements,

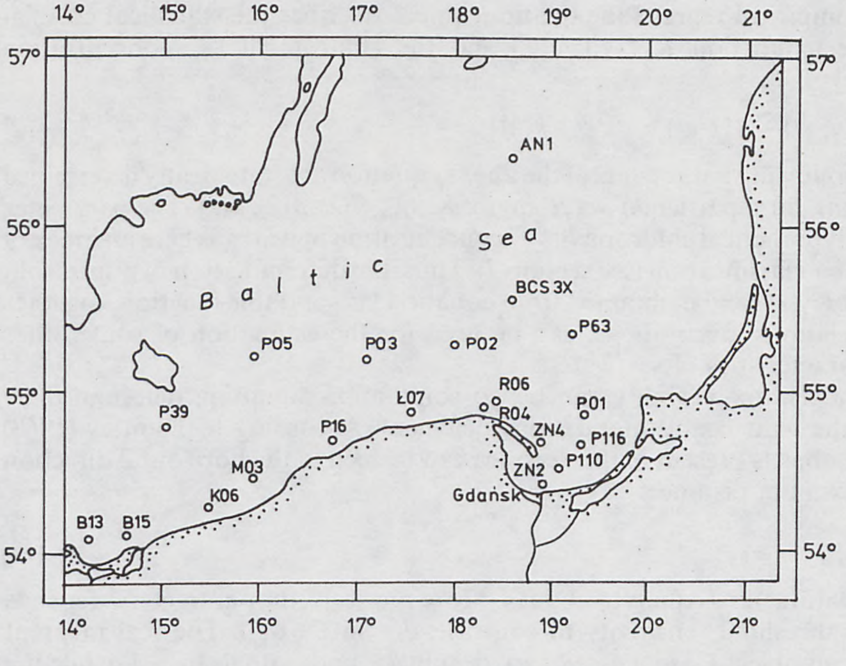


Fig. 1. Location of measuring stations in years 1986–1988
Central Baltic–AN1 (PEX station); Southern Baltic–P39, P05, P03, P02, BCS3X, P63, P01, R06; Coastal waters–K06, M03, P16, Ł07, R04; Gulf of Gdańsk–ZN2, P110, P116, ZN4; Pomeranian Bay–B13, B15

number of soudings and number of obtained data in particular cruises, are presented in Table 1. Additionally, some already published data, which had been collected in earlier cruises, were used in this paper and the sources of these data are indicated.

The *in situ* measurements of the light beam attenuation coefficient were made by means of a standard beam attenuation (transparency) meter, constructed at the Institute of Oceanology, and a principle of its operation is described, among others, by Jerlov (1976). A 15 watts bulb, manufactured by *Osram*, was a source of artificial light beam and a M12FS Carl Zeiss photomultiplier was a light detector in this instrument. The optical system placed in front of the detector gave a half-angle of acceptance θ about 0.5°. The path length between the watertight glass windows of the instrument which light had to cover in the investigated water was equal 0.97 m. A mechanism situated before the light detector contained a set of interference filters and allowed their remote selection. During the routine measurements, the filters of the maximum transmittance for the following wavelengths 425, 525, 620 nm were used. A half-width of transmittance band of filters, for the above given wavelengths, was about 4.5 nm. The measurements were based on *in situ* recordings of light transmittance as a function of depth:

$$T_m(\lambda, z) = \left(\frac{i_w}{i_a}\right), \tag{15}$$

Table 1. Mean values of light attenuation coefficient c and standard deviation σ for three selected wavelengths λ for various regions of the Baltic, measured during cruises in 1986–1988*

Period of time and station	Depth range [m]	$\lambda = 425$ nm				$\lambda = 525$ nm				$\lambda = 620$ nm			
		$\bar{c}(\lambda)$ [1/m]	σ [1/m]	N	n	$\bar{c}(\lambda)$ [1/m]	σ [1/m]	N	n	$\bar{c}(\lambda)$ [1/m]	σ [1/m]	N	n
1	2	3	4	5	6	7	8	9	10	11	12	13	14
						Central Baltic							
1986 April, 25–30	0–10	1.79	0.54	89	1869	.	.	.	.	.	.	.	.
	10–30	1.30	0.38	89	3649	.	.	.	.	.	.	.	.
AN1 (PEX)	30–50	0.84	0.25	89	3649	.	.	.	.	.	.	.	.
1986 May, 02–08	0–10	1.51	0.33	95	1995	.	.	.	.	.	.	.	.
	10–30	1.05	0.20	95	3895	.	.	.	.	.	.	.	.
AN1 (PEX)	30–50	0.25	0.18	95	3895	.	.	.	.	.	.	.	.
1988 June, 17–18	0–10	1.23	0.13	20	220	0.97	0.03	1	11	1.09	0.05	1	11
	10–30	1.10	0.23	20	420	0.78	0.19	1	21	0.85	0.16	1	21
AN1	30–50	0.57	0.13	20	420	0.38	0.01	1	21	0.51	0.01	1	21
						Southern Baltic							
1986 April, 03–06	0–10	0.67	0.31	26	286	.	.	.	.	0.51	0.23	27	297
	10–30	0.58	0.07	25	536	.	.	.	.	0.48	0.21	27	567
st. P2	30–50	0.60	0.29	24	496	.	.	.	.	0.43	0.21	27	567
1986 Sept, 23–27	0–10	1.19	0.19	12	132	0.72	0.15	12	132	0.82	0.12	12	132
	10–30	1.05	0.16	10	198	0.62	0.14	10	198	0.72	0.10	10	198
	30–50	0.86	0.14	7	140	0.50	0.10	7	131	0.59	0.10	7	140
1986 Oct, 20–27	0–10	1.25	0.11	7	77	0.87	0.10	7	77	1.08	0.10	5	55
	10–30	1.25	0.12	7	142	0.90	0.07	7	131	1.07	0.10	5	105
	30–50	1.18	0.17	6	122	0.82	0.13	6	121	0.99	0.14	5	100
1987 May, 01–06	0–10	2.17	0.35	13	143	1.75	0.29	13	143	1.89	0.32	13	143
	10–30	1.50	0.18	13	273	1.16	0.16	13	273	1.31	0.23	13	273
st. P1	30–50	1.26	0.10	13	140	0.93	0.08	13	149	1.10	0.17	13	145
1987 May, 13–17	0–10	1.41	0.16	11	121	1.21	0.50	11	121	1.39	0.19	11	121
	10–30	1.30	0.12	11	231	1.03	0.13	11	230	1.26	0.14	11	231
	30–50	1.13	0.12	8	171	0.86	0.14	8	169	1.13	0.15	8	172
1987 Sept, 09–14	0–10	1.87	0.95	10	110	1.06	0.38	10	110	1.16	0.39	10	110
	10–30	1.68	0.89	9	192	0.93	0.34	9	192	1.00	0.35	9	193
	30–50	0.91	0.31	6	118	0.47	0.22	6	117	0.58	0.20	6	117
1988 April, 20–25	0–10	0.90	0.31	7	77	0.80	0.49	7	77	0.83	0.26	7	77
	10–30	0.83	0.31	7	142	0.69	0.22	7	142	0.74	0.25	7	142
	30–50	0.64	0.31	6	126	0.50	0.23	6	126	0.56	0.23	5	124
1988 June, 15–20	0–10	1.95	0.64	35	395	1.13	0.05	2	22	1.72	0.51	2	22
	10–30	1.22	0.64	35	735	0.73	0.38	2	42	0.99	0.37	2	42
st. P1, P3	30–50	0.68	0.25	35	731	0.22	0.03	2	42	0.52	0.05	2	42
1988 Sept, 16–23	0–10	1.47	0.79	8	88	0.87	0.47	8	86	1.11	0.61	8	88
	10–30	1.06	0.28	7	147	0.64	0.15	7	147	0.87	0.25	7	147
	30–50	0.78	0.20	7	138	0.40	0.14	7	147	0.60	0.20	7	137

Table 1 continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Polish Coastal Waters													
1987 May, 15–17	0–10	1.80	0.34	4	44	1.53	0.32	4	44	1.61	0.39	4	44
	10–30	1.46	0.39	3	51	1.09	0.26	3	51	1.21	0.22	3	52
1987 Sept, 09–14	0–10	2.02	0.28	3	33	1.49	0.63	4	44	1.77	0.63	4	44
	10–30	2.00	0.31	3	53	1.36	0.42	3	57	1.42	0.44	3	58
1988 April, 23–24	0–10	3.00	0.14	2	22	2.58	0.31	3	33	2.61	0.27	3	33
Gulf of Gdańsk													
1986 Oct, 20–25	0–10	1.68	0.72	12	132	1.19	0.60	11	121	1.27	0.52	11	121
	10–30	1.43	0.16	9	172	0.98	0.11	8	168	1.09	0.09	8	168
	30–50	1.43	0.16	6	121	0.99	0.11	6	121	1.10	0.09	6	121
1987 May, 04–06	0–10	3.46	1.35	10	110	2.85	1.20	10	110	3.00	1.20	9	99
	10–30	1.53	0.43	10	196	1.17	0.41	10	196	1.33	0.20	9	174
1987 Sept, 13–14	0–10	1.73	0.31	6	66	1.13	0.20	6	66	1.18	0.17	6	66
	10–30	1.75	0.32	5	99	1.10	0.19	5	99	1.13	0.16	5	98
	30–50	1.84	0.26	2	32	1.09	0.16	2	35	1.16	0.14	2	34
1988 Sept, 16–23	0–10	1.22	0.36	10	110	0.67	0.29	9	99	0.83	0.31	9	99
	10–30	1.17	0.30	8	162	0.65	0.27	8	156	0.86	0.31	8	156
	30–50	1.06	0.30	7	130	0.57	0.28	7	130	0.84	0.35	7	130
Pomeranian Bay													
1986 Sept, 27	0–10	2.62	0.51	9	90	1.98	0.49	9	90	1.83	0.38	9	90

* Location of stations is shown in Figure 1. N – number of stations (vertical profiles), n – number of data

where i_w and i_a are the recorded signals which are proportional to the radiances L_r and L_0 (formula 3). Theoretically, the reference signal i_a should be recorded in the ideally clear, distilled water (thus, in water without any additions). In practice, it is extremely difficult to obtain the water which is needed for calibration and which would be very clean and would always have the identical optical properties. Thus, the measurement in the air considered as a reference medium is made. An additional advantage of this method is the fact that frequent and fast control of operational stability of the transparency meter can be made. This method is recommended, among others, by Jerlov (1976). A measurement of a reference signal in the air requires that the operational definition of the light attenuation coefficient (formula 3) be supplemented with a calibration coefficient k. The k coefficient depends on the geometry of the instrument and on the difference between the coefficients of light which is reflected by water and by air. In practice, equation (3) looks as follows:

$$k(\lambda)\, T_m(\lambda) = \mathrm{e}^{-c(\lambda) r}. \qquad (16)$$

As the coefficient relatively weakly depends on the wavelength λ, its value can be assumed as constant. Hence, basing on equations (15) and (16), the real value of light beam attenuation coefficient can be calculated from the following formula:

$$c(\lambda) = -\frac{1}{r}[\ln(k)+\ln(T_m)]. \tag{17}$$

In a case of single-beam transmittance meters of the type used by the authors, there are few methods leading to determination of the calibration coefficient k. These methods are described by Afonin and Spiridonov (1972), Lundgren (1976). In the presented work, the method described by Afonin and Spiridonov (1972) was applied and it is based on the calibration by means of grey filters with a known transmittance. The coefficient k which was repeatedly determined was equal to 0.85 ± 0.5. The error in the measurement of light attenuation coefficient was calculated and its value was 2% for c being in the range of most common values in the Baltic Sea ($0.5\ \mathrm{m}^{-1} < c < 1.5\ \mathrm{m}^{-1}$). The error was in the range 5 – 10% as the c value deviated from the above range. The values of errors were determined on the basis of analysis of the instrumental and environmental factors influence on the accuracy of readings of the beam transmittance meter. Among the instrumental and environmental factors, one may list: parameters of the optical system of the meter, characteristic of the electronic signal processing system, the accuracy of determination of a calibration correction factor, the scattering-absorption properties of the investigated sea (Afonin, Spiridonov, 1977; Ivanov, 1975; Kozlyaninov, 1981; Bishop, 1986).

The recording of i_w *and* i_a signals from the light detector system and signals from a depth sensor in the instrument were recorded with a frequency of 1 Hz during lowering of the meter into the sea. The signals were next converted, by means of 10-byte analog-to-digital converter, into the digital form. These data were then recorded on a computer disc. The subsequent handling of data included elimination of possible errors and finally interpolation of signal values at fixed depths (every 0.5 m or every 1 m).

4. Light attenuation spectrum

The only window in the spectrum of electromagnetic waves transmittance in the oceanic waters lies in the visible light band and a deep minimum of attenuation is in the band 475 nm (Ivanov, 1975). In the cleanest oceanic waters, for example in the Sargasso Sea or in subtropical parts of the Pacific Ocean, the light attenuation coefficient reaches the minimum values ($0.02 - 0.03\ \mathrm{m}^{-1}$) at the wavelength $\lambda = 475$ nm. The absorption of longer waves by water and molecular scattering of shorter waves are the main reasons of a rapid increase of coefficient $c(\lambda)$ in clean water as moving away from the 475 nm band (Jerlov, 1976). Thus, the differentiation of sea water transparency towards the electromagnetic waves takes place mainly in the visible light band and in near ultraviolet. This differentiation results from different concentrations of organic components and suspended particles, mentioned in the introduction, in the sea water. These components interact with the visible and near ultraviolet light band. That is why the spectral distributions of attenuation of visible and ultraviolet radiation in the Baltic Sea are strongly differentiated in space and strongly variable in time. The characteristic examples of such spectra for the Baltic (solid lines) and the clean Sargasso Sea (dotted line) for comparison are shown in Figure 2. Additionally points being the mean values measured at selected wavelengths in different seasons and regions of the Baltic Sea are shown too.

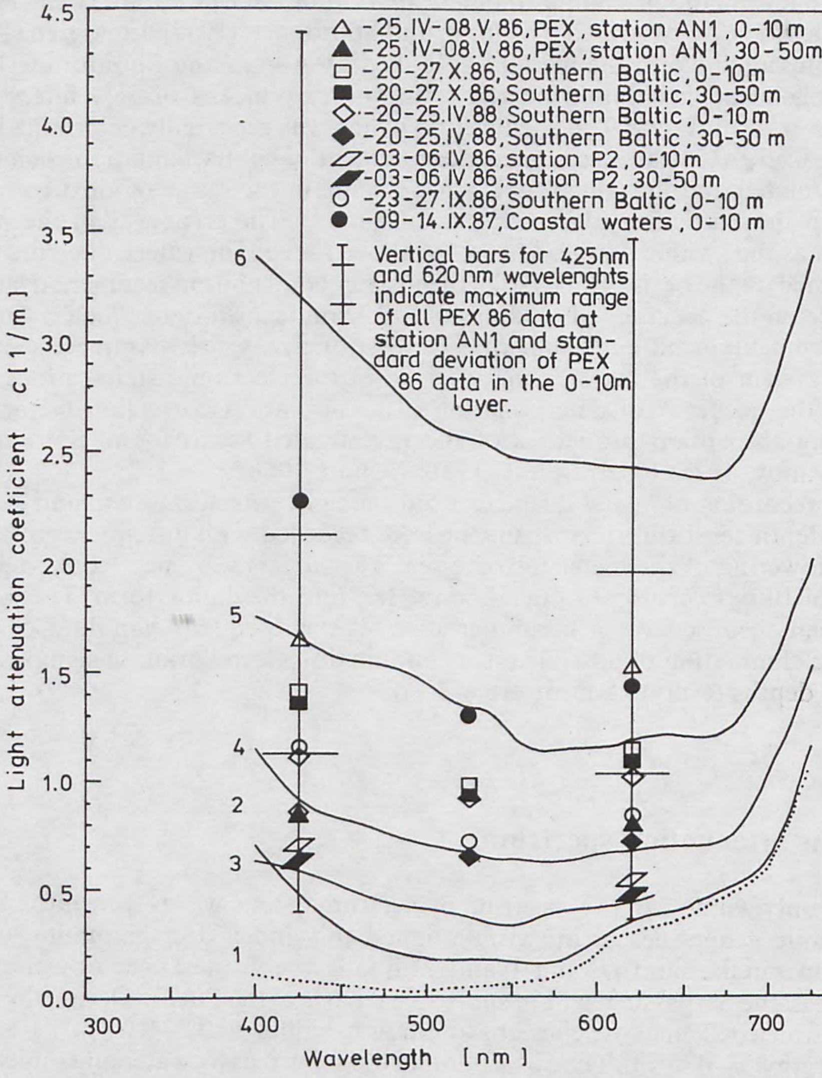


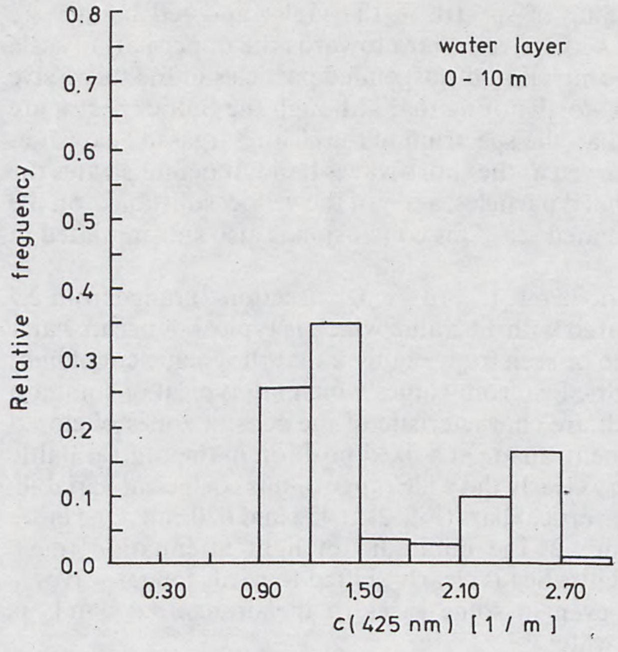
Fig. 2. Typical spectra of the beam attenuation coefficient in Baltic waters (solid lines) in comparison to clear Sargasso Sea waters (dotted line).
Points indicate mean values measured in different regions and seasons and different water layers. For location and number of samples see Figure 1.
1 – Sargasso Sea, (Kopelevich *et al*, 1974); 2 – Baltic, at SW from Gotland, V 74, depth 50 m (Lundgren, 1976); 3 – Baltic, station P2, IV 86, depth 14 m; 4 – Baltic, Gulf of Gdańsk, III 76, depth 30 m (Gohs *et al*, 1978); 5 – Baltic, Gulf of Gdańsk, III 76, depth 6 m (Gohs *et al*, 1978); 6 – Baltic, Gulf of Gdańsk, VI 76, depth 1 m (Gohs *et al*, 1978)

The reasons for upward bending of spectra in the violet and red band were already explained. The shift of successive spectra towards the upper part of scale arises from the increase of concentration of suspended particles in the successive case of investigated water. It is worth noting that although the Baltic spectra are located much higher (Fig. 2.) than the spectrum of the clean Sargasso Sea water, they are not always strongly curved at the short-waves band. It demonstrates the dominating influence of suspended particles, and not the yellow substance, on the light attenuation in the investigated sea. This conclusion is also substantiated in the section 7.

The estimated values of ratio $(c-c_w)_{380}/(c-c_w)_{655}$ (section 2) range from 2.7 to 3.0 and are higher as compared with 1.8 value which is typical of ocean water (acc. to Jerlov, 1976). It can also be seen from Figure 2 that the coefficient of light attenuation changes in the Baltic Sea from values which are typical of common oceanic waters to values which are characteristic of the coastal zones of closed seas. The time series measurements made at a fixed position in the central Baltic (PEX 86 experiment) shows very clearly the wide range of this coefficient variability and this is presented by the vertical bars (Fig. 2) at 425 and 620 nm. One more thing can be seen from Figure 2: the minimum of light attenuation (max. transparency) existing in the Baltic Sea is clearly shifted towards longer waves *ie* towards the green/yellow or even in some cases to the orange/red band, as compared with clear oceanic water.

5. Spatial variability

The spatial variability of the Baltic waters is known only in outline as there have been made only scarce monitoring measurements (Dera, 1967; Lundgren, 1976; Gohs *et al*, 1978; Nikolaev, 1987). The most transparent waters are usually observed in the mid-water layer ($\approx 30-50$ m) in the open Southern and Central Baltic, and in particular towards south-east from Gotland (Hojerslev, 1974) the light attenuation coefficient c reaches the minimum values in the entire Baltic. The coefficient c has minimum values between 0.20 and 0.25 m^{-1} at $\lambda = 525$ nm. In the violet light band, the minimum values are close to those observed in oceanic waters of the type II (acc. to optical classification given by Jerlov, 1964) and they range from 0.3 to 0.4 m^{-1} at $\lambda = 425$ nm. Hence, the coefficients c are over 10 times higher in the Baltic waters than in the Sargasso Sea. Figure 3 illustrates the characteristic empirical statistic distribution of the coefficient c (425 nm) for the surface layer $0-10$ m and an intermediate layer $30-50$ m in the Baltic Sea. The transparency differentiation in the vertical profile depends on the size distribution and also on the concentration of suspended particles, and the latter parameters depend on numerous hydrophysical and biological factors in the sea. However, a tendency of decrease in suspended particle concentration as well as decrease in average size of particles can be observed below the euphotic zone, but at some distance from the sea bottom (see for example Jerlov, 1959; Jakubovich *et al*, 1979). Thus, the surface layer and also the near-bottom zone are less transparent than the intermediate waters. This is well illustrated by the vertical profiles $c(z)$ shown in Figure 4. These profiles were selected as typical from among



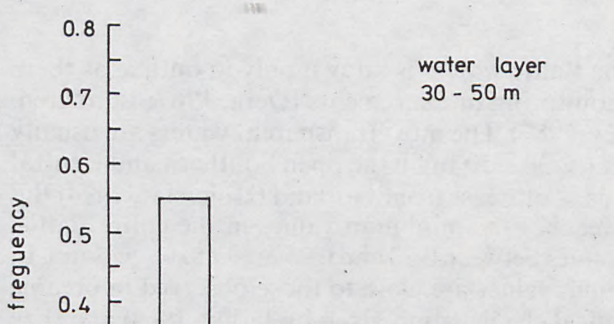


Fig. 3. Distribution of light attenuation coefficient *c* (425 nm) in open Baltic waters June 15–20 1988, stations AN1, P01, P03

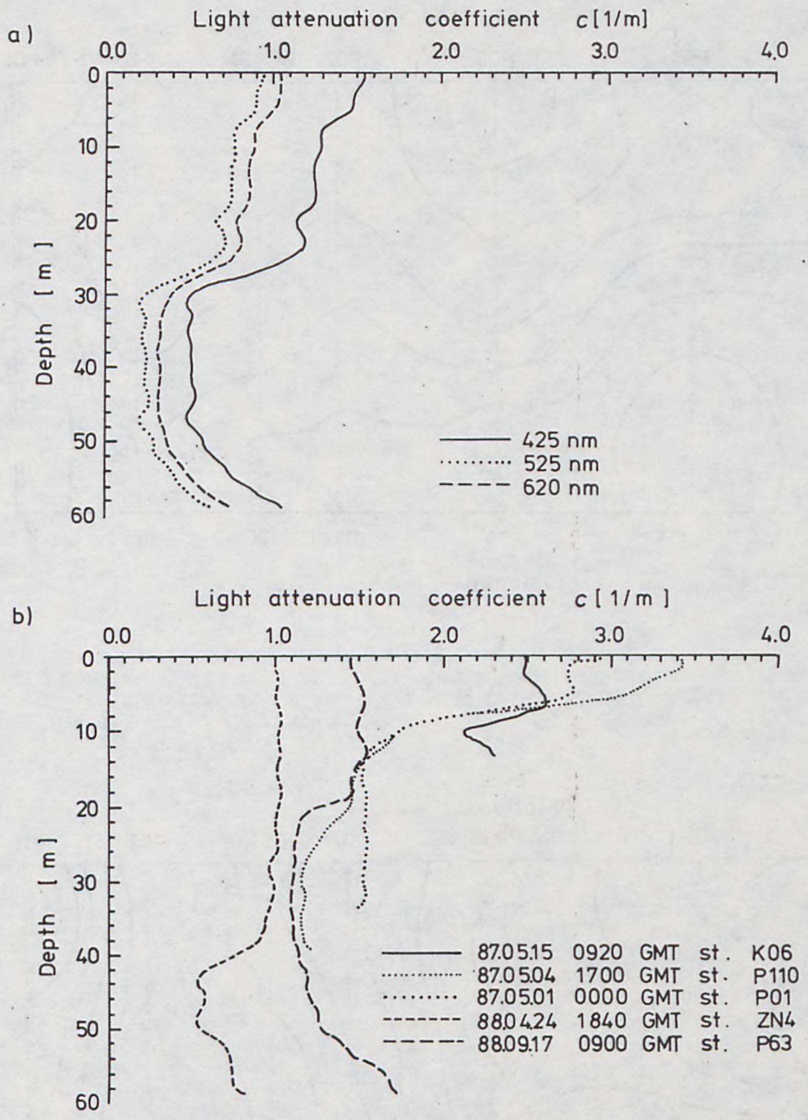


Fig. 4. Typical vertical profiles of light attenuation coefficient in Baltic waters
a) station P03, 20.09.88 for wavelengths 425, 525, and 620 nm;
b) open and coastal waters for wavelength 425 nm

numerous results acquired in open waters of the Baltic. These vertical profiles differ, however, from each other as their shape depends on a region and season of investigation. In many cases the strong inflows of contaminated waters originating either from the biggest Polish rivers: Vistula and Odra, or from other estuaries of the Southern Baltic may affect the vertical profiles and the horizontal distribution of isolines representing the coefficient *c* (425 nm). This is shown in Figures 5 and 6. Waters in the vicinity of estuaries and also in bays are usually less

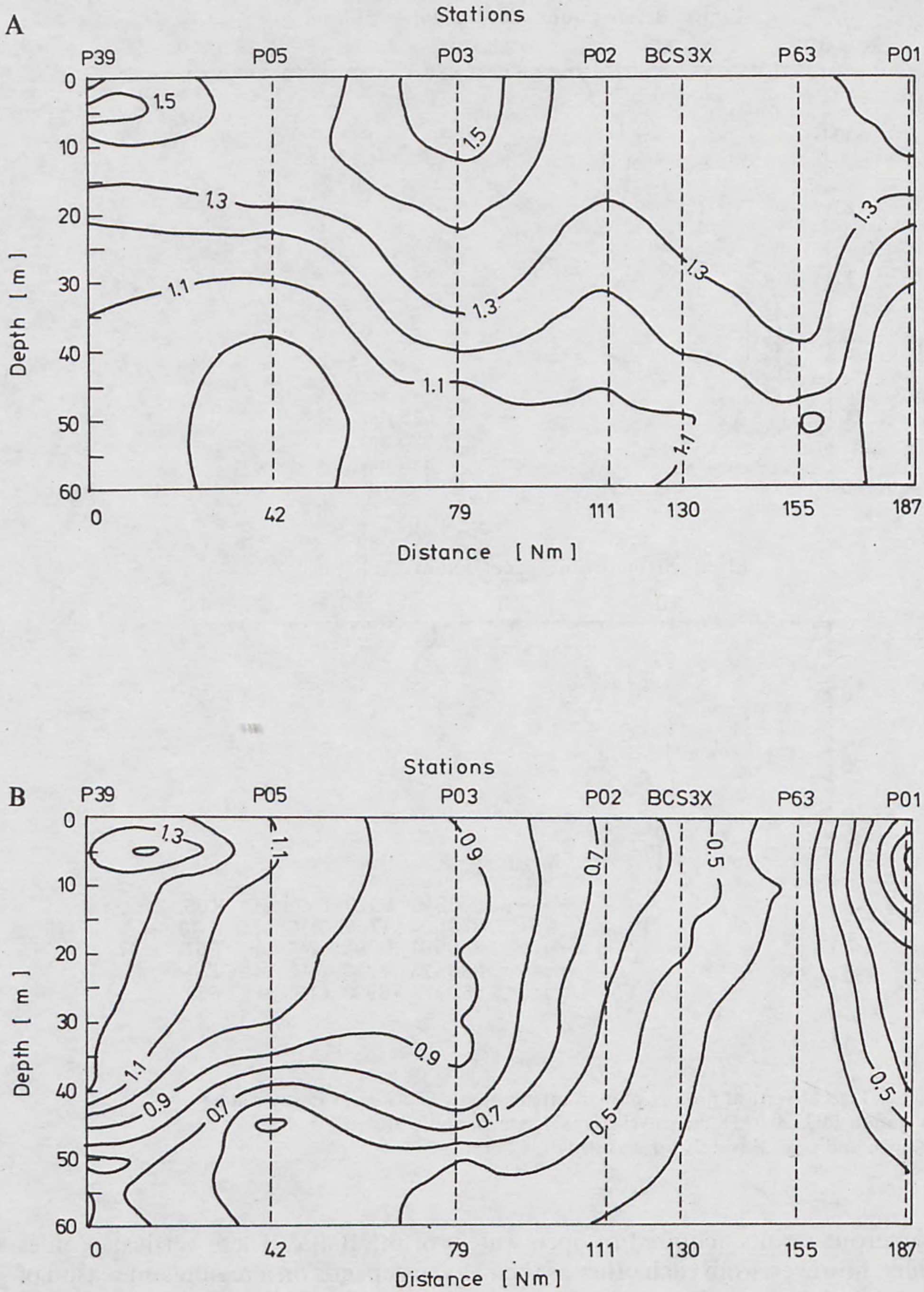
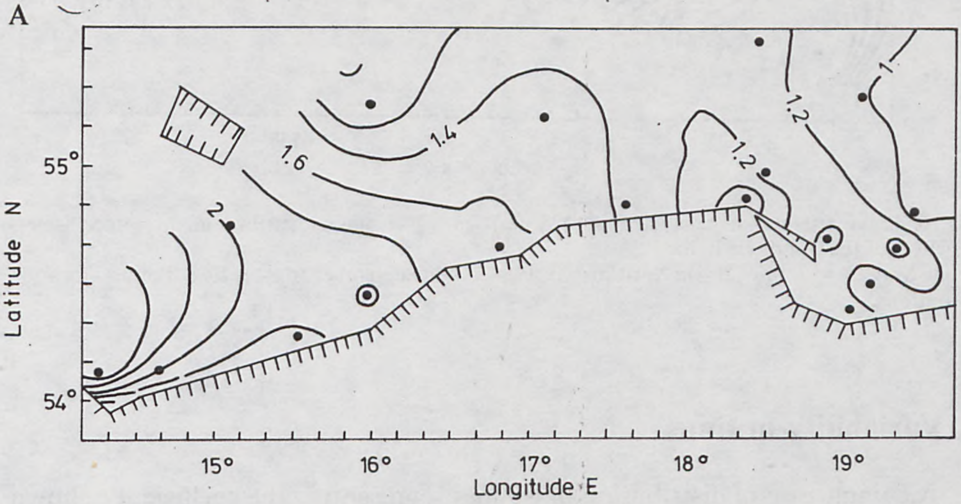


Fig. 5. Light attenuation coefficient c (425 nm) [m^{-1}] – isolines distribution in a vertical cross-section along the vessel route
A – in May 13–17, 1987, B – in April 20–25, 1988. Points – location of stations

transparent: values of c (425 nm) exceeding 1.5 m^{-1} or even 2 m^{-1} are typical of coastal waters which are contaminated with the impurities described at the beginning of this paper. This type of waters, as can be seen from Figures 5 and 6, is also observed in the open Baltic. A detailed interpretation of distribution of isolines $c(\lambda)$ will be possible following the investigation of correlation between this coefficient and the concentration of different substances in water, including chlorophyll, suspended matter, yellow substance.

A



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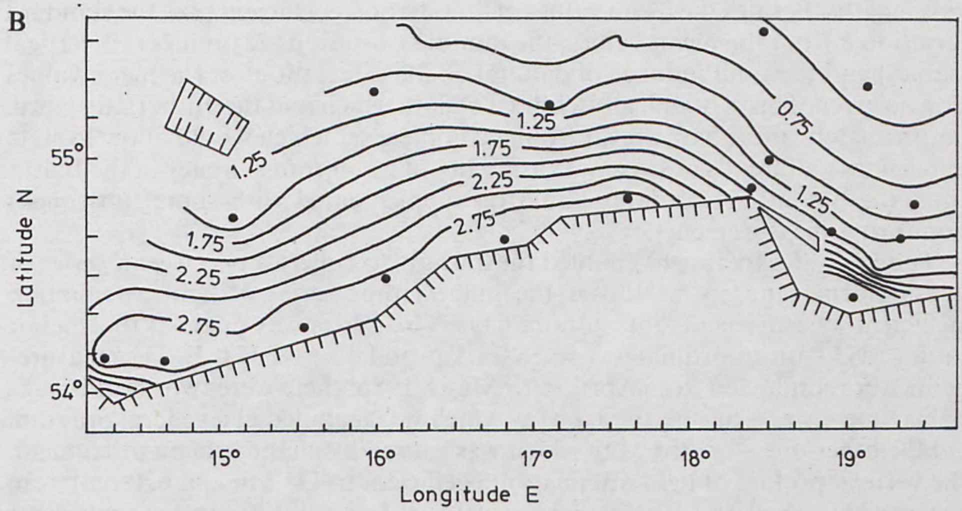


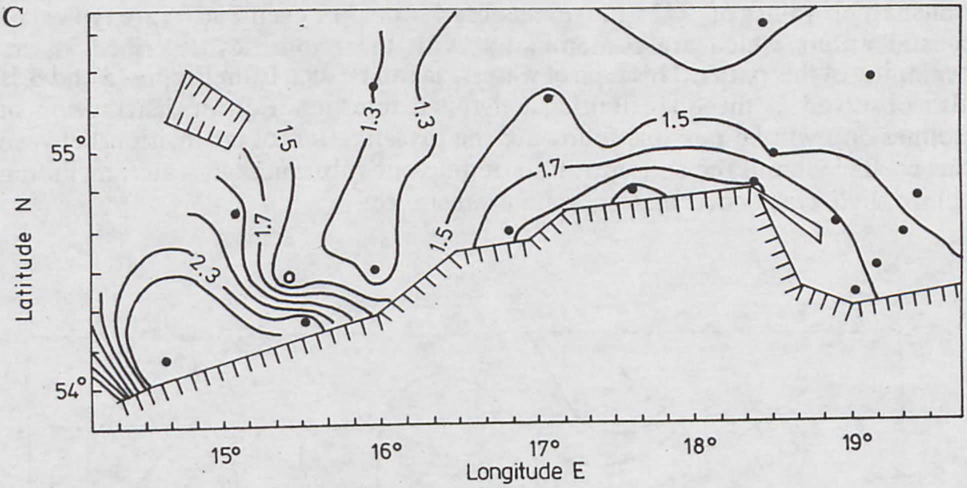


Fig. 6. Light attenuation coefficient c (425 nm) $[m^{-1}]$ – isolines distribution in surface waters (0–1 m) of the Southern Baltic
A – in May 13–17, 1987, B – in April 20–25, 1988, C – in September 16–23, 1988. Points – location of stations

6. Variability in time

A comparison of distribution of isolines representing the coefficient c shown in Figures 5 and 6 allows to see significant differences in water transparency measured in different time periods. This time variabilities were compiled in Table 1 which contains the mean values of c measured in different seasons and regions; the measurements were made in three selected water layers and three selected wavelengths. Besides the mean values of attenuation coefficient $c(\lambda)$, the standard deviation σ from the mean values, the number of stations N (number of vertical profiles) and the total number of data taken for calculations of the mean values are also given. This is practically a full set of data which is at the authors' disposal. Unfortunately, these data are far from a complete set which would allow to state regularities and trends in seasonal variability of water transparency in the Baltic. Thus, the present set of data should be supplemented with some subsequent monitoring measurements.

The PEX 86 experiment enabled the authors to collect a two-weeks' series of measurements and so far this is the longest time series of light attenuation coefficient measurements the authors have. This series was made at the anchor station AN1 with co-ordinates: $\lambda = 56°25.3'$ N and $\phi = 18°37.0'$ E. The measurements were conducted from April 25 to May 8 1986; there were two short breaks in this time series – one on the 1st May which was included in a general program and the other one – on 3rd May which was caused by a failure of an instrument. The vertical profiles of light attenuation coefficient c (425 nm and 620 nm) were measured *in situ* every 1.5 hour and every 0.5 m. In total, 176 vertical profiles (or about 19,500 of single readings) of c value for given wavelengths were obtained. Measurements were carried out from the surface down to 55 m (last recording

5 m above the bottom). The obtained results of *c* coefficient showed a wider range of its variability as compared with the literature data hitherto collected in the Baltic Sea. Among the characteristic features of observed variability of transparency of the Baltic waters there are:

(i) usually higher variability of transparency in the near-surface layer compared to deep layers,

(ii) strong variability of transparency within hours and days.

This is illustrated, as an example, in Figures 7 and 8. The statistical characteristics

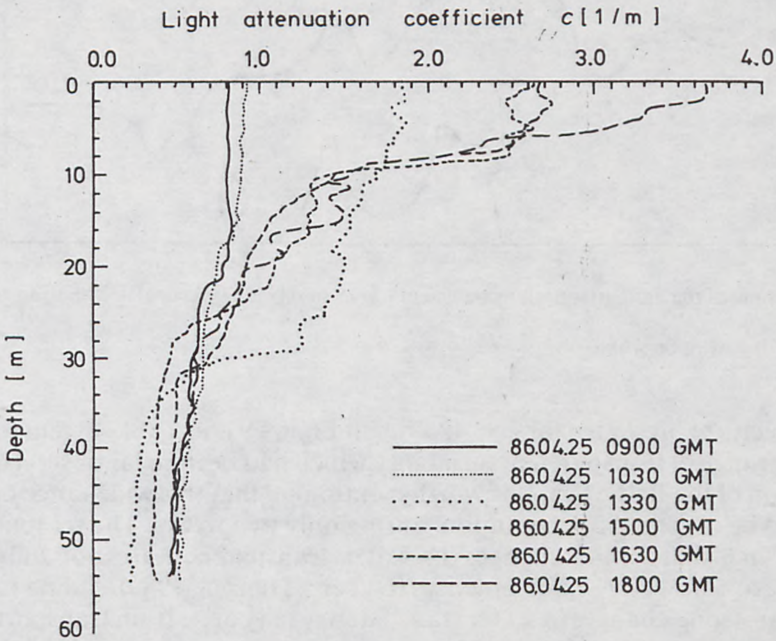
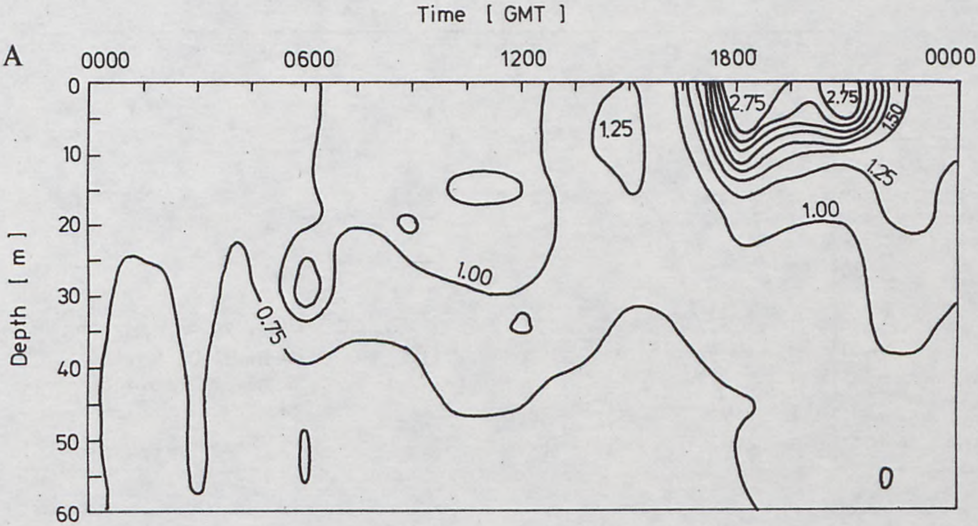


Fig. 7. Example of a rapid change in the vertical light attenuation *c* (425 nm) profiles at station AN1 (PEX 86)



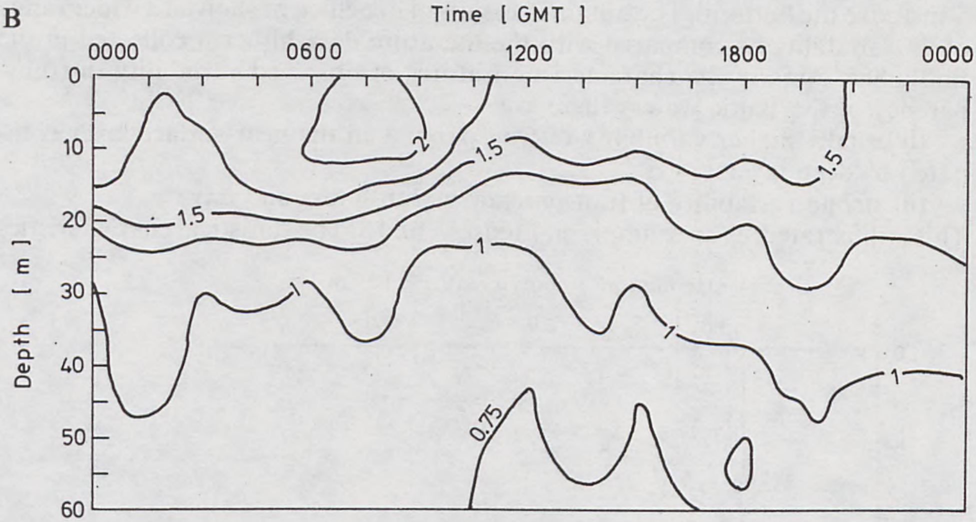
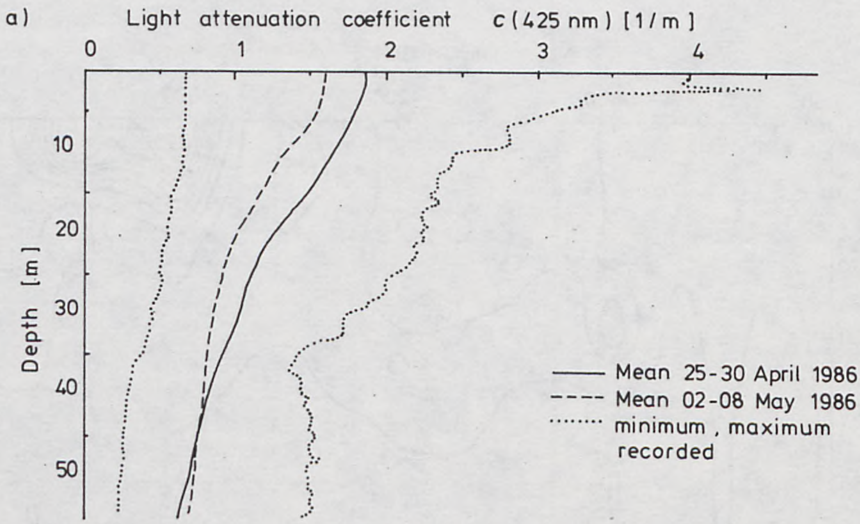


Fig. 8. Variation in time of the light attenuation coefficient c (425 nm) [m^{-1}], vertical distribution at station AN1 (PEX 86)
A – April 26, 1986; B – May 06, 1986

of the results which are presented for $\lambda = 425$ nm in Figure 9 and Table 1 seem to characterize the range of transparency variability which had been so far observed in the open region of the Baltic Sea. It is worth mentioning that this wide range of variability could be observed at one station, during only two weeks. The reasons for such large and sharp time changes in water transparency are not fully explained. There are, however, many premises (Dybern, Hansen, 1989) leading to a conclusion that strong changes in water transparency may arise from transport with currents of not fully described nonhomogeneous water masses (patches).



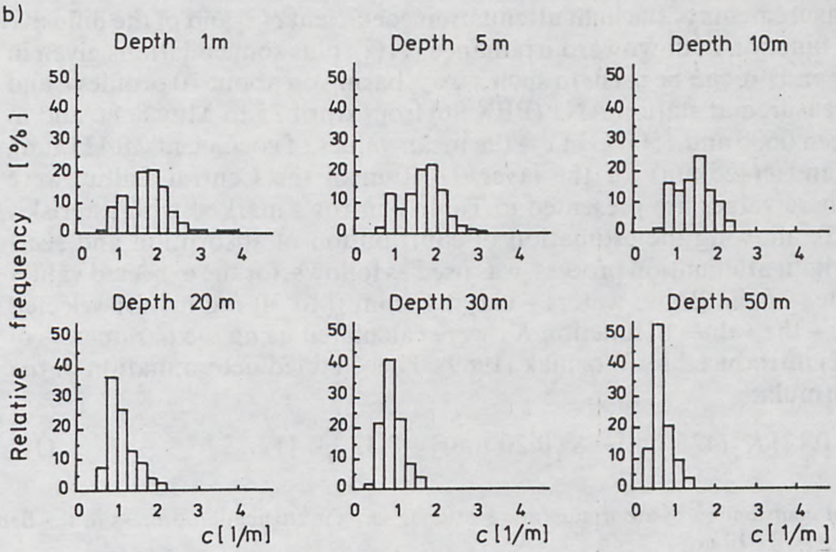


Fig. 9. Light attenuation coefficient *c* (425 nm) at station AN1 (PEX 86)
a) mean vertical distribution; b) histograms at standard levels

These turbid patches are rich in organic matter. Formation of these patches, or in other words, formation of such big horizontal nonhomogeneities in the open sea can be attributed both to the inflows of turbid waters from the polluted coastal zone and to the local biological processes. The latter ones are mainly primary production together with uneven influence of hydrodynamic and physico-chemical factors on the phytoplankton distribution (Sildam *et al*, 1987).

7. Components of light attenuation

The evaluation of contribution of absorption and scattering to the light attenuation process, for particular wavelengths, is an essential optical characteristic of water. The technical problems related both to measurements of light attenuation coefficient in the sea and measurements of absorption coefficient in the absorption/scattering medium cause that there are only scarce data allowing this evaluation. Basing on investigations performed in 1972–1974 in the Gulf of Gdańsk (Dera *et al*, 1978) it was ascertained that the mean values of probability of photon survival (see formula 11) are ω_0^- (425 nm) = 0.54 and $\bar{\omega}_0$ (525 nm) = 0.61. It follows from this statement that the contribution of scattering in the light attenuation process for the violet light band (425 nm) was, in the investigated region, equal on average 54% while in the case of green light band (525 nm) it amounted to 61%. It was stated that out of 46% which fall to absorption attenuation at λ = 425 nm, as much as 20% arises from absorption by suspended particles and only 32% from absorption by yellow substance dissolved in water. It supports the dominating role of suspended particles in the process of light attenuation in the investigated waters. There is lack of such data for the open Baltic waters but for estimation of this dominating role the results of simultaneous measurements of the light attenuation coefficient $c(\lambda)$ and of the diffusive attenuation function of downward irradiance $K_{\downarrow}(\lambda)$, plus some relations given in formulae (4) and (9), can be used. In such a way, basing on about 70 profiles c and $K_{\downarrow}$ values measured at station AN1 (PEX 86) from April 25 to May 8, 86 and in hours between 0600 and 1500 GMT – the mean values of coefficients a(425 nm), b(425 nm), and c(425 nm) for the layer 0–10 m of the Central Baltic, were obtained. These values are presented in Table 2 in rows marked with asterisks. Formula (12), allowing the estimation of contribution of absorption and scattering in the light attenuation process, was used as follows: for the expected values of the B index of the Baltic waters – varying from 0 to 30 mg/m^3 for selected wavelengths – the values of function $K_{\downarrow}$ were calculated using the parameters of equation (12) introduced by Woźniak (1989). This enabled determination of the following formula:

$$B = 22.33 \pm 0.17[K_{\downarrow}(425 \text{ nm}) - K_{\downarrow}(620 \text{ nm})] + 3.42 \pm 0.11, \quad (18)$$

Table 2. Calculated contribution of absorption and scattering in light attenuation process in the Baltic waters, for depth range 0–10 m

Period of time	$\lambda = 425$ nm				$\lambda = 620$ nm			
	$\bar{c}(\lambda)$ [1/m]	$\bar{a}(\lambda)$ [1/m]	$\bar{b}(\lambda)$ [1/m]	$\bar{\omega}$	$\bar{c}(\lambda)$ [1/m]	$\bar{a}(\lambda)$ [1/m]	$\bar{b}(\lambda)$ [1/m]	$\bar{\omega}$
Central Baltic								
*1986 April, 25–30	1.70	0.49	1.21	0.71	.	.	.	.
1986 April, 25–30	1.70	0.44	1.26	0.74	.	.	.	.
*1986 May, 02–08	1.56	0.46	1.10	0.71	.	.	.	.
1986 May, 02–08	1.56	0.21	1.35	0.86	.	.	.	.
1988 June, 17–18	1.23	0.40	0.83	0.68	1.09	0.30	0.79	0.73
Southern Baltic								
1986 April, 03–06	0.67	0.42	0.25	0.37	0.51	0.30	0.21	0.40
1986 Sept, 23–27	1.19	0.66	0.53	0.44	0.82	0.38	0.44	0.53
1986 Oct, 20–27	1.25	0.43	0.82	0.66	1.08	0.31	0.77	0.72
1987 May, 01–06	2.17	0.55	1.62	0.74	1.89	0.35	1.54	0.82
1987 May, 13–17	1.41	0.28	1.13	0.80	1.39	0.25	1.14	0.82
1987 Sept, 09–14	1.87	1.08	0.79	0.42	1.16	0.52	0.64	0.55
1988 April, 20–25	0.90	0.33	0.57	0.64	0.83	0.27	0.56	0.67
1988 June, 15–20	1.95	0.50	1.45	0.75	1.72	0.33	1.39	0.81
1988 Sept, 16–23	1.47	0.65	0.82	0.56	1.11	0.38	0.73	0.66
Polish Coast								
1987 May, 15–17	1.80	0.45	1.35	0.75	1.61	0.32	1.29	0.80
1987 Sept, 09–14	2.02	0.52	1.50	0.74	1.77	0.34	1.43	0.81
1988 April, 23–24	3.00	0.69	2.31	0.77	2.61	0.39	2.22	0.85
Gulf of Gdańsk								
1986 Oct, 20–25	1.68	0.71	0.97	0.58	1.27	0.40	0.87	0.69
1987 May, 04–06	3.46	0.77	2.69	0.78	3.00	0.42	2.58	0.86
1987 Sept, 13–14	1.73	0.88	0.85	0.49	1.18	0.46	0.72	0.61
1988 Sept, 16–23	1.22	0.69	0.53	0.44	0.83	0.39	0.44	0.53
Pomeranian Bay								
1986 Sept, 27	2.62	1.17	1.45	0.55	1.83	0.55	1.28	0.70

*calculated by measurements of c and K with application of formula (9) which provides the dependence between the B index of water and $K_{\downarrow}$ function values difference $K_{\downarrow}(425\ \text{nm}) - K_{\downarrow}(620\ \text{nm})$.

A considerable simplification was introduced next. It was assumed that the light scattering on suspended particles in the Baltic Sea is, for the mentioned wavelength range, practically not selective in relation to these waves. Thus, the increment of attenuation coefficient $c(425\ \text{nm}) - c(620\ \text{nm})$ is approximately equal the increment of absorption coefficient $a(425\ \text{nm}) - a(620\ \text{nm})$. Further on, basing on formula (9) and then on the differences $a(425\ \text{nm}) - a(620\ \text{nm})$, the differences $K_{\downarrow}(425\ \text{nm}) - K_{\downarrow}(620\ \text{nm})$ were calculated. Using formula (18) the indexes of B type B for the investigated waters were found. Having the index of type of water for the series of measurements listed in Table 1 it was possible to calculate, using formulae (9) and (12), the absorption coefficient $a(\lambda)$, and basing on formula (4) – to calculate the scattering coefficients $b(\lambda)$. The results of these estimations are presented in Table 2. The discrepancy between the results obtained by these two methods of estimation can be seen from comparison of the first with the second row and the third with fourth row in Table 2. Theoretically, these results should be in agreement. However, it can also be stated that this discrepancy is not too large for the indirect method of estimation, based on formula (12), to be considered not useful for a rough estimation.

As there were made some assumptions and simplifications in estimation of data in Table 2, the far reaching conclusions should not be drawn from this table. However, it is clear that out of 20 different series of measurements (described in Table 1), 15 series showed the mean values of parameter $\bar{\omega} > 0.5$ for $\lambda = 425$ nm; 9 series – $\bar{\omega} > 0.7$. Undoubtedly it demonstrates that there is a dominating contribution of scattering in the visible light attenuation process in the investigated waters of the Baltic Sea. The variability of parameter $\bar{\omega}$, thus the variability of the ratio b/c is as large as the variability of the light attenuation coefficient itself. This confirms the dynamic variability of concentrations of particular substances described in the introduction interacting with the light in the Baltic Sea.

8. Final conclusions

The water transparency in the Baltic Sea shows a very strong variability in time and space and the factors causing this variability are generally described in the introduction. Such a variability is characteristic of regions heavily polluted with suspended particles and organic substances originating from external sources. The polluted and strongly eutrophicated rivers are the main sources. The values of light attenuation coefficient are lowest, in the case of these waters, in the green/yellow light band. Thus, for this light band the Baltic waters have the highest transparency. For the wavelength $\lambda = 525$ nm and for the cleanest waters occurring in the Southern Baltic the minimum value of this c coefficient, in the intermediate layer 30 – 50 m, is about 0.22 to 0.3 m^{-1}. The near-surface layer (0 – 10 m) has the lowest values of transparency and the mean values of light attenuation coefficient c (525 nm), calculated for the data collected in particular cruises, range in this layer from 0.7 m^{-1} to 1.5 m^{-1}. This variation is shown in

Table 1. The maximum values of c coefficient (525 nm) occasionally reach the value over 3 m^{-1}. For the other wavelengths, the values of light attenuation coefficient are higher, as can be seen in Table 2 and also in Table 1. The reported figures show a scale of variability of optical properties of water masses in the Southern Baltic. This variability can be called patchiness of waters (Dybern, Hansen, 1989).

The estimated data concerning the contribution of absorption and scattering in the light attenuation in Baltic waters showed that the contribution of scattering on suspended particles dominated. This is presented in Table 2 from which the probability of photon survival ω_0, is seen to most often, exceed the value 0.5.

The presented data concerning the light attenuation by absorption allowed to conclude about the conditions of light propagation in the Baltic Sea (acc. to equations 1, 3, and 9). Basing on formulae (13) and (14) the conclusions concerning the underwater visibility can also be drawn. For example, using formula (13) and assuming the light attenuation coefficient to be c(525 nm) = 0.2 m^{-1}, which is sometimes observed in the cleanest waters of the Baltic, it can be calculated that the probable maximum distance from which the large dark object can be seen will reach about 20 m. This distance may, however, be shorter (3 – 6 m) and this fact takes place when the c coefficient changes, in the upper 10-meter level, from 0.7 m^{-1} to 1.5 m^{-1}.

A more detailed characteristic of optical variability of water properties in the Southern Baltic Sea requires further statistical investigations. Determination of factors generating this variability requires complex investigations and searching for the correlation between optical properties of water and the concentrations of suspended particles, chlorophyll, and organic substances.

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