Spatial and temporal changes in some optical parameters in the southern Baltic

OCEANOLOGIA, No. 33
pp. 87 1992.
PL ISSN 0078–3234

Marine optics
Undersatellite regional data
Optical properties
Baltic waters

Jerzy Olszewski,
Sławomir Sagan,
Mirosław Darecki
Institute of Oceanology,
Polish Academy of Sciences,
Sopot

Manuscript received June 25, 1992, in final form April 23, 1993.

Abstract

The spatial and temporal changes of the light beam attenuation coefficient and colour index, measured in the southern Baltic in 1987–90, are presented. Noticeable regularities in the changes, suggesting some spatial – seasonal classification of the waters investigated, are pointed out and discussed. Grouping the results into separate spring and autumn sets, as well as into open and coastal water sets, yields a quite good correlation between blue, green and red light beam attenuations, and between the depth of the euphotic zone and the colour index.

1. Introduction

Throughout the spring and autumn seasons of 1987–1990, systematic measurements of hydrooptical parameters in Baltic waters were carried out on board the r/v ‘Oceania’. The research work was done within the framework of the monitoring programme of the Polish Economic Zone. One result of this work is a considerable amount of data on the spatial and temporal distributions of some optical properties of water in this area.

The 4-year period was too short to produce a definitive statistical description of the variability of these parameters. However, it was possible within that time-interval to observe and describe some regular characteristics. The trends thereby revealed are of importance in planning future experiments, *e.g.* the organization of satellite monitoring of the environment. In this particular case, a knowledge of average environmental parameters is essential for assessing whether observed parameter values differ from typical ones.

2. Materials and methods

Measurements were made twice a year from 1987 to 1990: in spring (March – May) and in the autumn (September). Stations were chosen in accordance with the system used by the Institute of Water Management in Gdynia. Their location is presented in Table 1.

Table 1. Location of the measurement points

Name	Latitude N	Longitude E
in coastal zone		
P101	54° 32.1'	18° 36.3'
92A	54° 35.0'	18° 40.0'
ZN2	54° 23.0'	18° 57.5'
P110	54° 30.0'	19° 06.8'
P116	54° 39.1'	19° 17.6'
ZN4	54° 40.0'	18° 50.0'
R6	54° 57.3'	18° 24.9'
R4	54° 53.0'	18° 22.2'
Ł7	54° 50.0'	17° 32.1'
P16	54° 38.0'	16° 48.0'
M3	54° 27.0'	15° 59.0'
K6	54° 15.4'	15° 32.0'
B15	54° 04.6'	14° 41.5'
B13	54° 04.0'	14° 15.0'
in open sea zone		
P1	54° 50.0'	19° 20.0'
P63	55° 21.0'	19° 03.5'
P140	55° 33.0'	18° 24.0'
P2	55° 17.5'	18° 00.0'
P3	55° 13.0'	17° 04.0'
P5	55° 15.0'	15° 55.0'
P39	54° 44.5'	15° 08.0'

The following optical parameters were measured: the light-beam attenuation coefficient c at 425, 525 and 620 nm, the downward irradiance attenuation coefficient K_d at 425 and 525 nm, and the colour index CI at a depth of 1 m. Also calculated was the euphotic depth Z_e, defined here as the depth at which the irradiance level of the maximum light transmission wavelength (520–550 nm in the Baltic) is 1% of that reaching the surface. Standard transmission, irradiance and colour index meters were used, all made at the PAS Institute of Oceanology in accordance with the definitions of the parameters measured (Jerlov, 1968; Dera, 1983). In the case of the colour index measurements, the standard definition of the parameter (Jerlov, 1974) was modified: the straightforward ratio of upward radiances L_u at 450 and 520 nm was replaced by the ratio normalized relative to the simultaneously measured downward irradiance E_d. This yielded the equation:

$$CI = \frac{L_u(450)/L_u(520)}{E_d(450)/E_d(520)}. \qquad (1)$$

Such a normalization minimizes the influence of the light conditions above the water surface.

From the material collected, the $c(425)$ nm and CI parameters are used in the presentation the results. The high correlation coefficients between $c(425)$, $c(525)$ and $c(620)$, presented later in this paper, make such a reduction possible. The colour index CI is important because of its potential usefulness in satellite data analysis.

3. Results

3.1. Light-beam attenuation coefficient

Light is attenuated by both the water itself and its constituents. The light-beam attenuation coefficient for 425 nm is the sum of the light absorption and scattering coefficients, and can be divided into three main components:

- Attenuation caused by molecular scattering and absorption by water. Its value is independent of on-going biophysical conditions.
- Weak selective spectral attenuation caused by suspended matter, mainly from scattering at these suspensions.
- Strong selective spectral attenuation caused by dissolved organic matter, mainly by absorption, rising exponentially towards the short-wavelength range (Jerlov, 1976; Dera, 1983).

The attenuation coefficient for 425 nm is independent of chlorophyll *a* absorption; its variability is positively correlated with suspended matter and yellow substance concentrations.

Measurements were carried out from the sea surface down to a depth of 50 m. From the biological and optical points of view, this range covers the active layer of Baltic waters. In the analysis of temporal variability the investigated area was divided into the coastal zone and the open sea waters (Tab. 1). As regards the attenuation coefficient, the water body was further divided into three layers: surface water (0–10 m), intermediate water (10–30 m) and deep water (30–50 m). The variability observed during 1987–90 is illustrated in Figure 1. Despite the relatively short time span, several typical features can be distinguished:

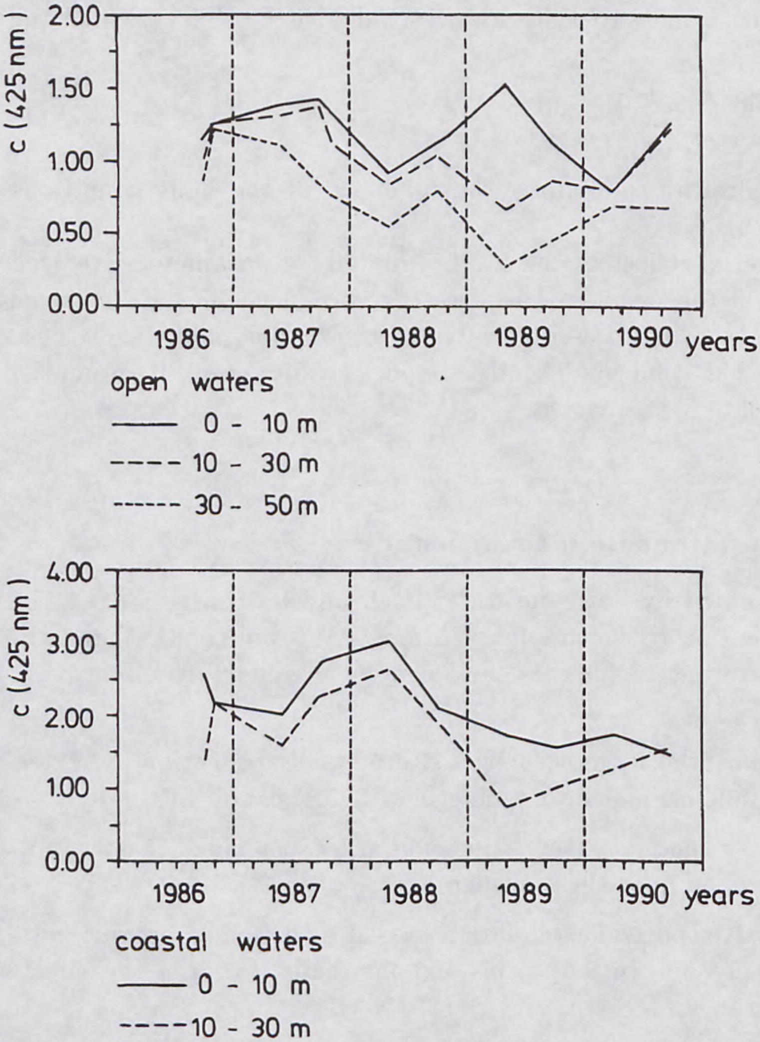


Fig. 1. Temporal changes in mean blue light beam attenuation coefficient (months of measurements as in Table 2)

- The variability was periodic. Except in 1987, spring values of $c(425)$ in open water down to 30 m were low; autumn values were higher.
- The nature of this variability was the same in all three depth layers (again – with the exception of spring 1987).

- The variability in the coastal zone was the reverse of that in the open sea waters.

This seasonal variability becomes much more clear-cut when the data are grouped according to the time of year in which they were collected – see the 'box and whiskers' plot (Fig. 2) (Press *et. al.*, 1987). As can be seen, the open-sea values of $c(425)$ (0.50–0.60 m^{-1}) fall to a minimum in April. The variability of $c(425)$ in the upper 0–30 m layer is similar and is suggestive of higher values during the summer and lower values in the autumn. The statistical distribution of $c(425)$ in the autumn is different from that in spring and summer. These differences are less at greater depths. Within the surface layer a significant positive asymmetry of distribution is observed.

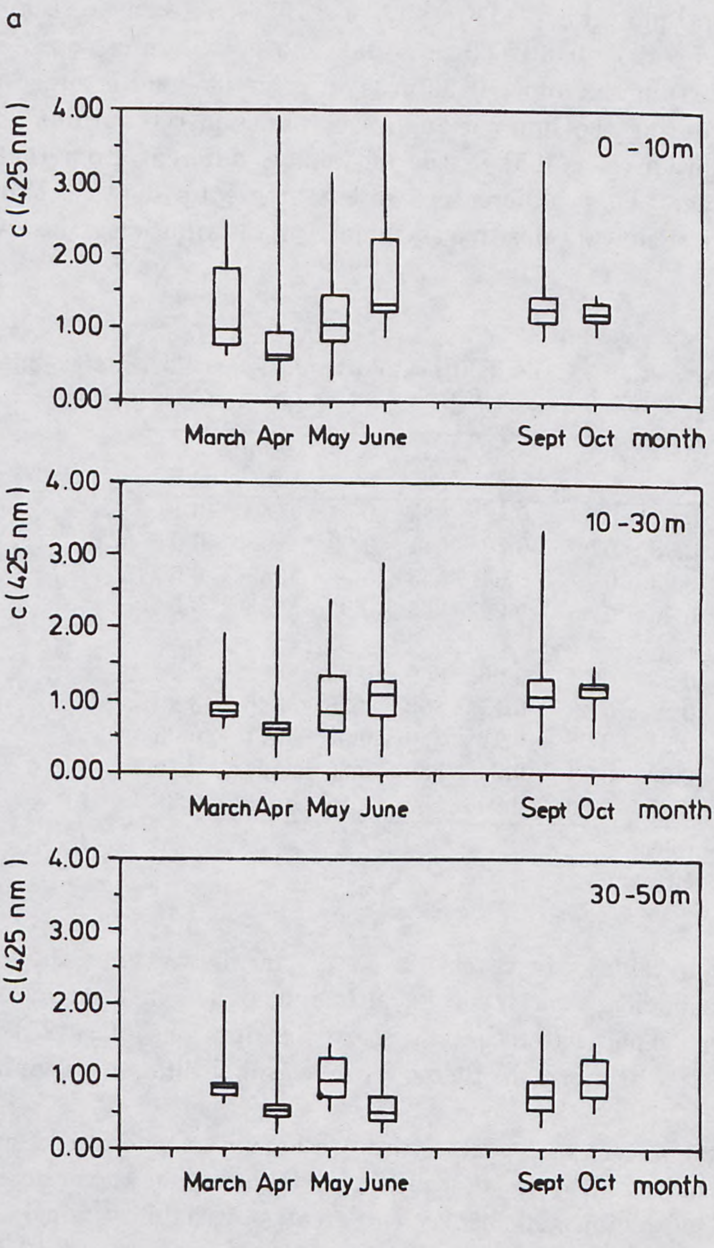
Table 2. Linear regression for the light beam attenuation coefficients at different spectral bands: $c(\lambda) = c(425\text{ nm})\ A + B$

	$\lambda = 525$ nm				$\lambda = 620$ nm			
Date	N	r	A	B	N	r	A	B
May 87	686	0.91	0.66	0.17	685	0.94	0.80	-0.14
Apr. 88	622	0.98	0.99	-0.19	611	0.99	0.90	-0.04
Apr. 89	575	0.93	0.79	-0.04	443	0.94	0.85	-0.06
Mar. 90	723	0.96	0.86	-0.22	665	0.93	0.83	-0.06
Oct. 86	768	0.95	0.74	0.06	668	0.92	0.62	0.24
Sept. 87	755	0.91	0.49	0.17	808	0.95	0.46	0.29
Sept. 88	891	0.91	0.68	-0.12	860	0.94	0.71	0.05
Sept. 89	642	0.98	0.74	-0.04	589	0.95	0.63	0.19
Sept. 90	664	0.97	0.50	0.04	669	0.97	0.68	0.06

N – quanta of samples,
r – correlation coefficient.

Light attenuation values can reach 4.0 m^{-1}. In the autumn the range of variability is smaller (0.8–1.2 m^{-1}), although higher values may occur sporadically. In deeper water the statistical distributions of $c(425)$ from all months are close to normal. Below 30 m seasonal differences virtually disappear.

In the coastal waters such regularities are hardly in evidence. Surface waters are characterized by mean values of c higher than those observed in the investigated region and display the greatest variability and highest maxima (up to 4.0 m^{-1}). The same features are observed in the 10–30 m layer as in the open water, but with significantly higher levels of variability of c (0.8–2.0 m^{-1}).


a
4.00
3.00
2.00
1.00
0.00
c (425 nm)
0 - 10m
March Apr May June Sept Oct month
10 - 30m
30 - 50m

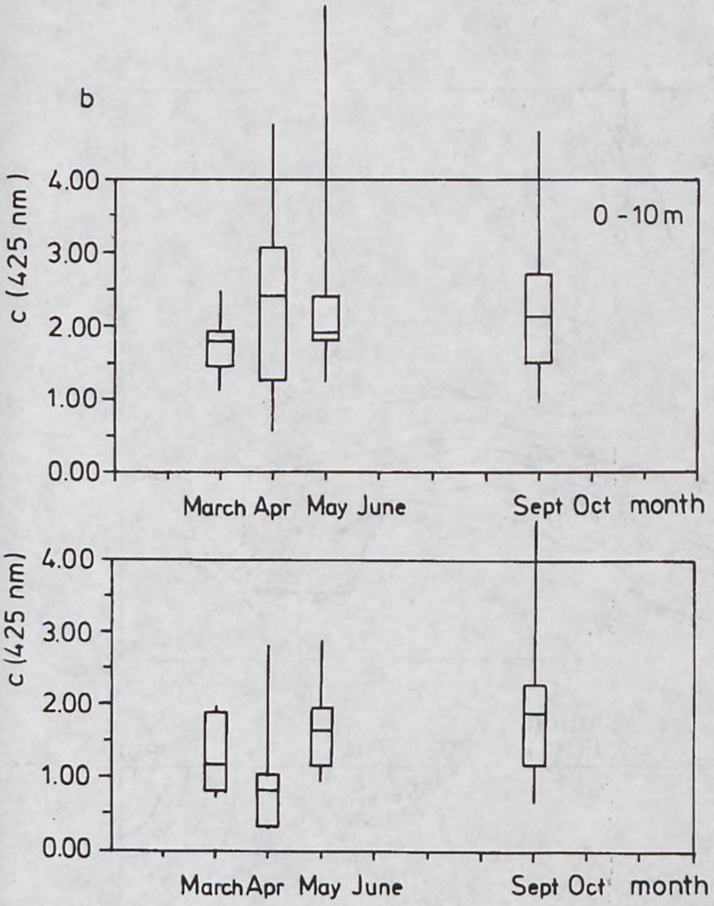
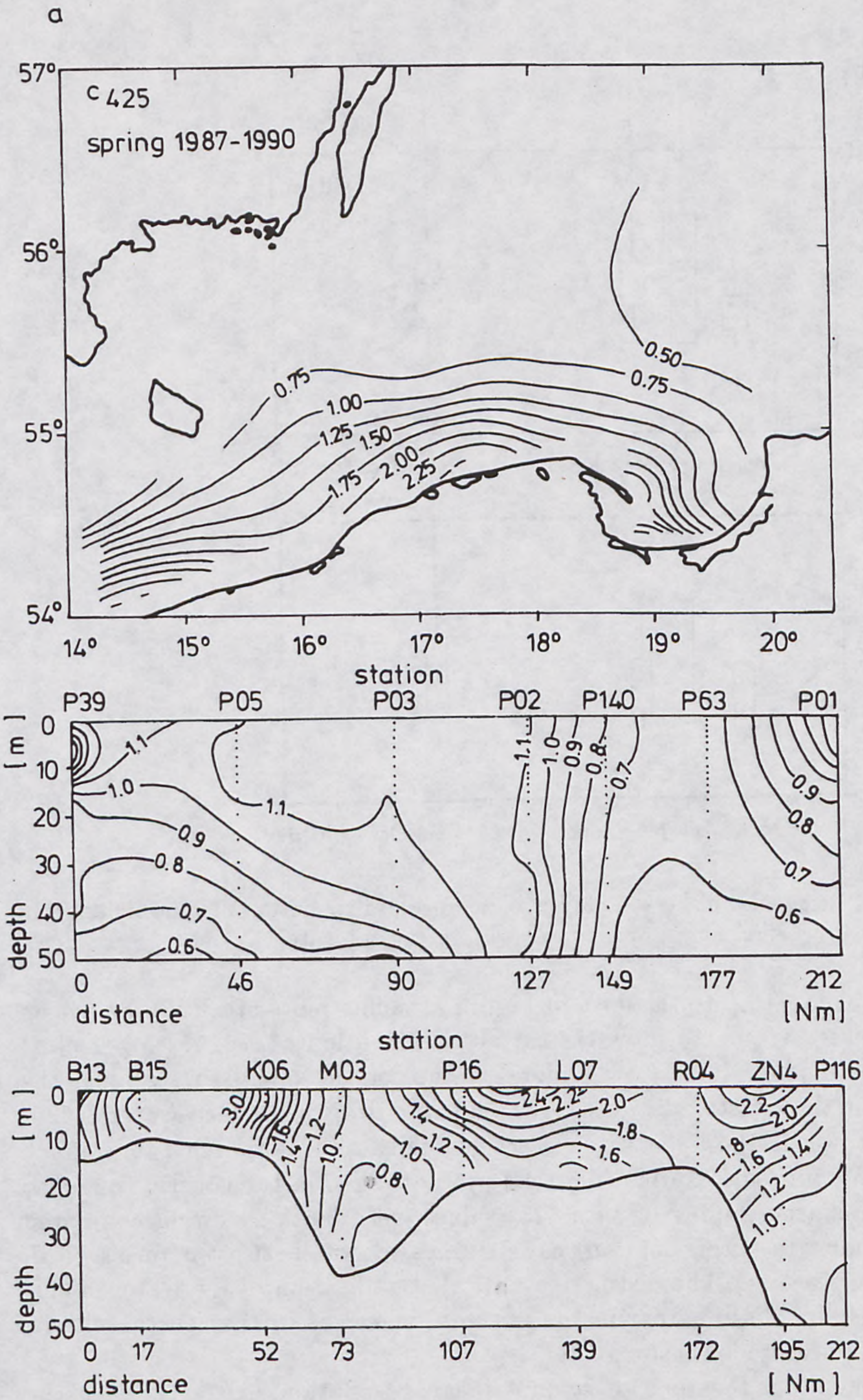


Fig. 2. 'Box and whiskers' analysis of temporal distribution of blue light beam attenuation coefficient: in open waters (a), in coastal waters (b)

Supplementary to the data in Figure 2, isoline plots of $c(425)$ have been drawn (Fig. 3). These show the surface distribution of $c(425)$ (upper plot) and two cross-sections (lower plots) – one for the open-sea stations, the other for the coastal stations. Although the drop in surface water $c(425)$ values towards the open sea area is generally quite apparent, it is much more pronounced in spring. Vertical profiles taken in the coastal zone also reveal a sharper falling off in $c(425)$ values with depth in spring compared to autumn. In spring, no vertical stratification of $c(425)$ was observed in the open sea area. The distinctive optical stratification of the water in this area was already apparent in the autumn, when, as in the coastal waters, $c(425)$ values are lower at greater depths.

As mentioned earlier, a strong linear correlation exists between the light attenuation coefficients for 425 nm and those for 525 and 620 nm.



a
c 425
spring 1987-1990
57°
56°
55°
54°
14°
15°
16°
17°
18°
19°
20°
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
station
P39
P05
P03
P02
P140
P63
P01
depth [m]
0
10
20
30
40
50
1.1
1.0
0.9
0.8
0.7
0.6
distance
0
46
90
127
149
177
212
[Nm]
station
B13
B15
K06
M03
P16
L07
R04
ZN4
P116
depth [m]
3.0
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
distance
0
17
52
73
107
139
172
195
212
[Nm]

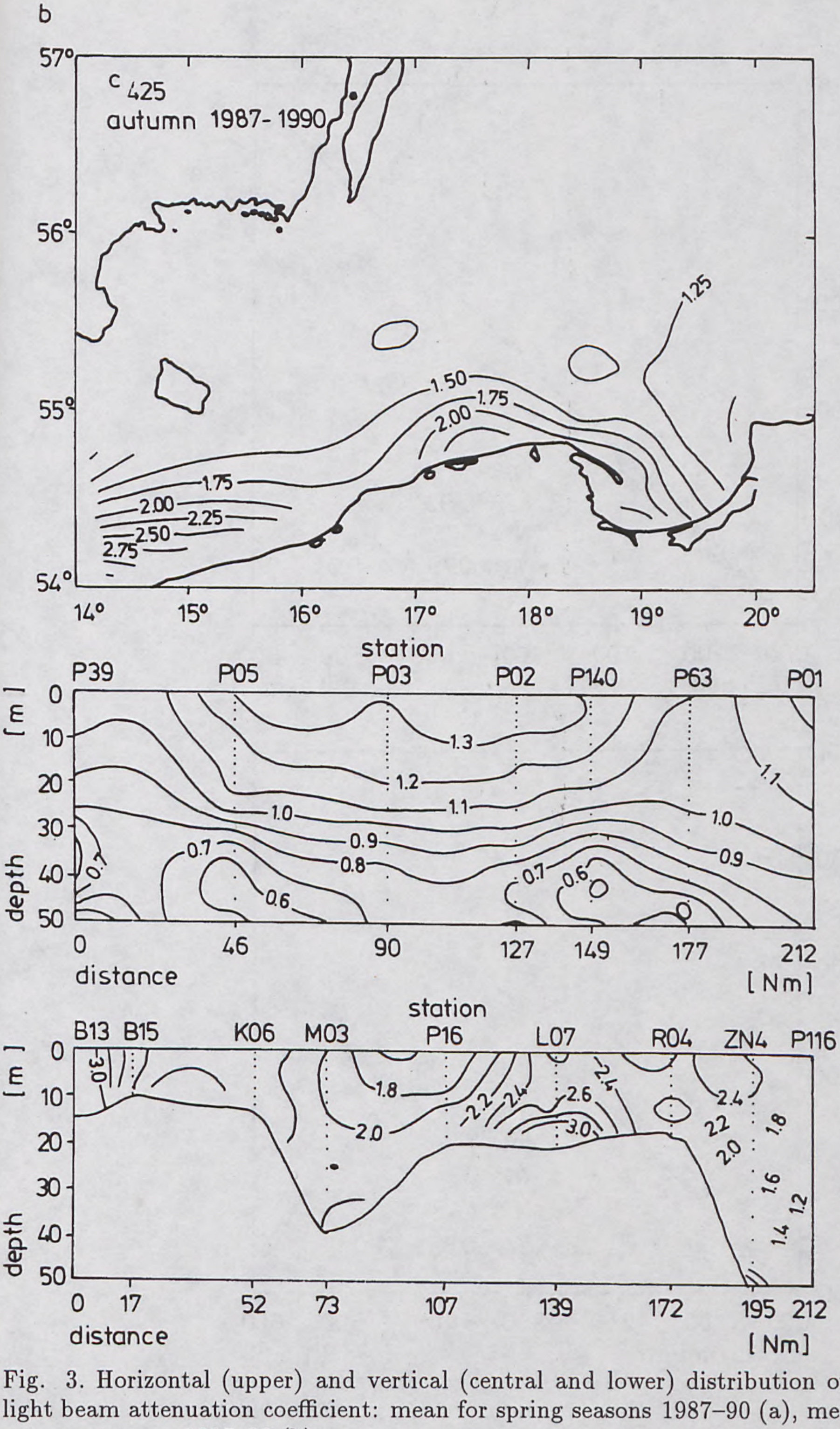
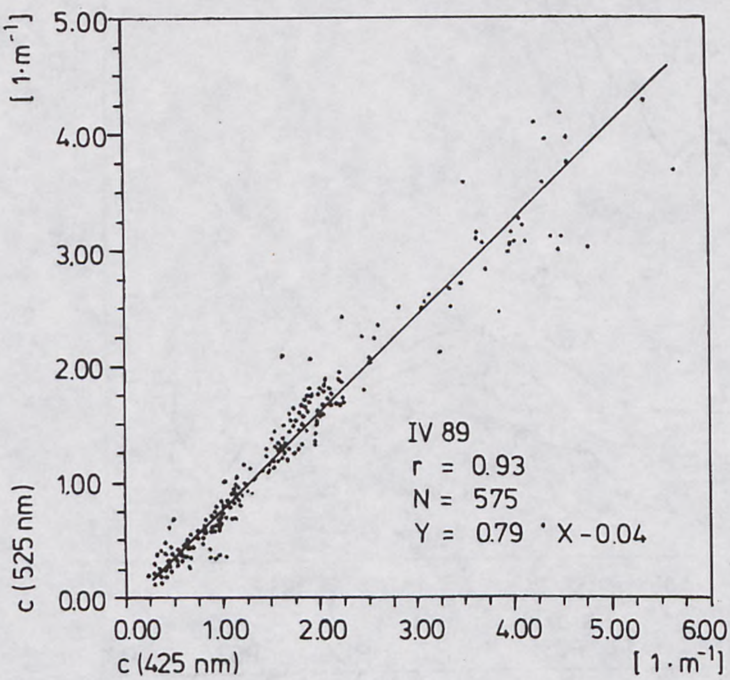
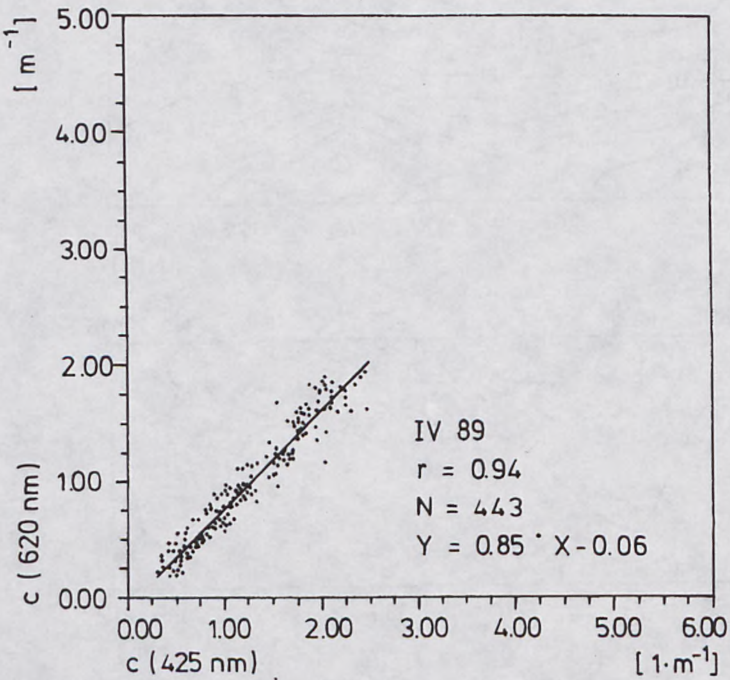


Fig. 3. Horizontal (upper) and vertical (central and lower) distribution of blue light beam attenuation coefficient: mean for spring seasons 1987–90 (a), mean for autumn seasons 1987–90 (b)

a


c (525 nm) [1·m⁻¹]
5.00
4.00
3.00
2.00
1.00
0.00
0.00 1.00 2.00 3.00 4.00 5.00 6.00
c (425 nm) [1·m⁻¹]
IV 89
r = 0.93
N = 575
Y = 0.79 · X - 0.04


c (620 nm) [m⁻¹]
5.00
4.00
3.00
2.00
1.00
0.00
0.00 1.00 2.00 3.00 4.00 5.00 6.00
c (425 nm) [1·m⁻¹]
IV 89
r = 0.94
N = 443
Y = 0.85 · X - 0.06

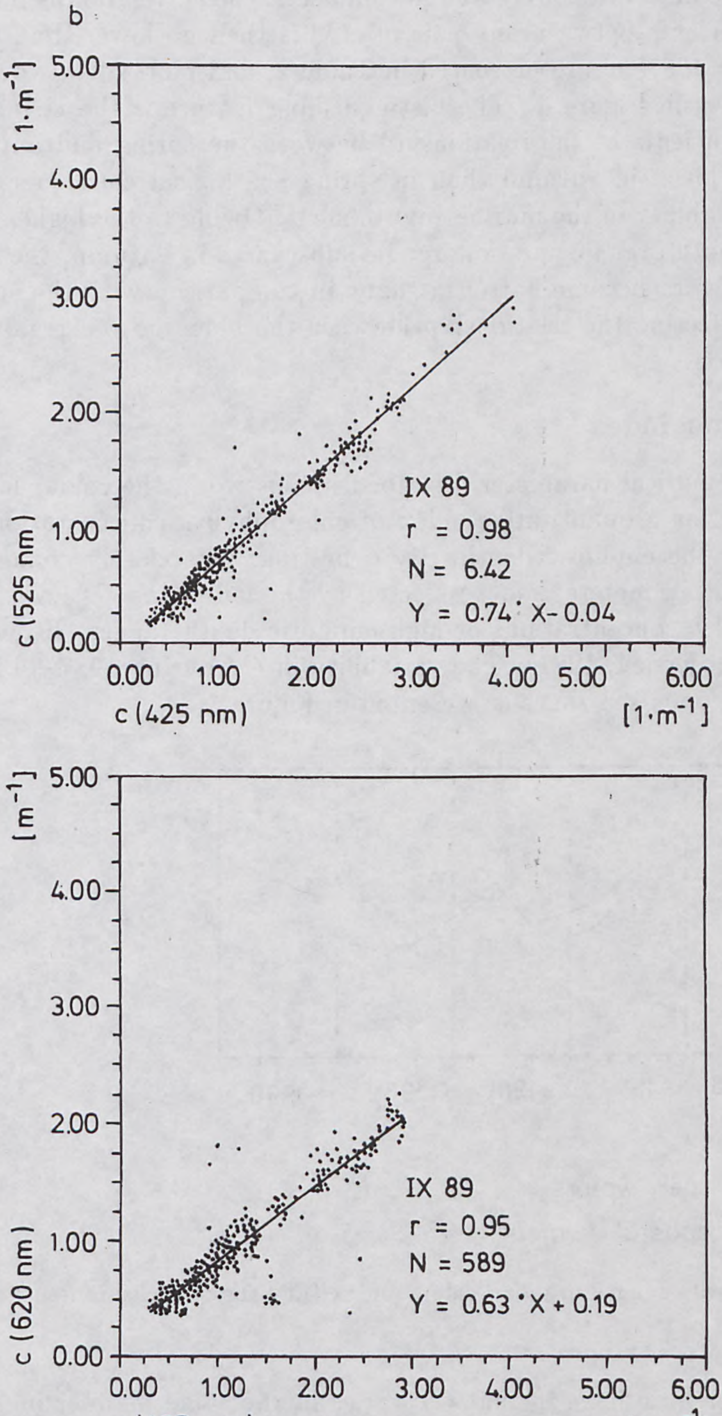


Fig. 4. Example of linear regression lines for blue/green (upper) and blue/red (lower) light beam attenuation coefficients: spring 1989 (a), autumn 1989 (b)

By dividing the data into spring and autumn sets, the correlation is improved: the coefficients between any pair of $c(\lambda)$ is then no lower than 0.96. The results for 1987–90 are presented in Table 2, and plots of this dependence are shown in Figure 4. The distinguishing feature is the change in the linear coefficients of the relationship between the spring and autumn seasons. It is lower in autumn than in spring – a logical consequence of the annual variability of the marine environment. Owing to the higher concentration of both organic and nonorganic substances in autumn, the light attenuation spectra become flatter in shape in comparison with the spring season, thus affecting the relationship between the blue and red regions of light attenuation.

3.2. The colour index

The second optical parameter described in this work, the colour index, may be treated as a quantitative index of chlorophyll *a* concentration, or as an index of the euphotic depth. By definition, it is closely connected with the above parameters, a fact reflected by the fall in the CI level with low chlorophyll *a* concentrations or high euphotic depth ranges (Hojerslev *et. al.,* 1977; Hojerslev, 1981). The variability in CI during 1987–90 both for coastal and open sea zones is presented in Figure 5.

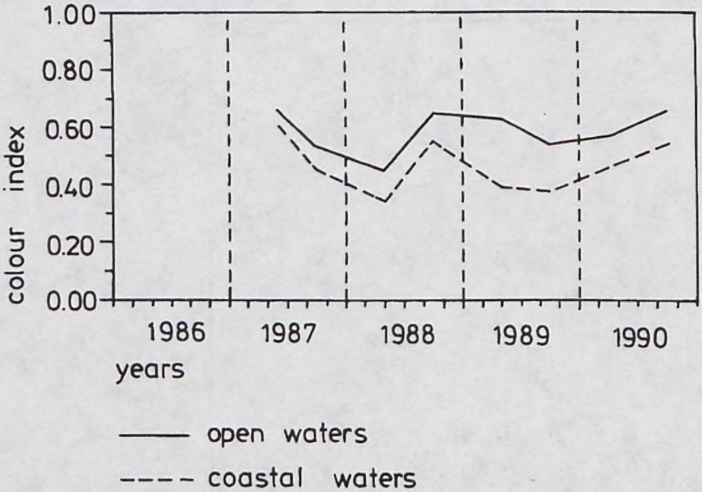


Fig. 5. Temporal changes in mean colour index (months of measurements as in Table 3)

What is worth noticing is that CI varies in the same manner in both zones; however, mean values are higher by about 0.12 in the open sea area. This means that its annual variability cycle is independent of distance from

Table 3. Linear regression for the logarithmic relationship between colour index CI and euphotic zone depth Z_e: $\log Z_e = \log A + B \log CI$

Date	N	r	A	B
Apr. 88	21	0.80	44.7	1.29
Apr. 89	21	0.91	42.7	1.38
Mar. 90	20	0.81	65.7	1.73
88–90	62	0.87	48.7	1.41
Sept. 88	21	0.62	22.0	0.58
Sept. 89	21	0.86	23.82	0.57
Sept. 90	14	0.36	19.56	0.32
88–90	56	0.74	22.0	0.52

N – quanta of samples,
r – correlation coefficient

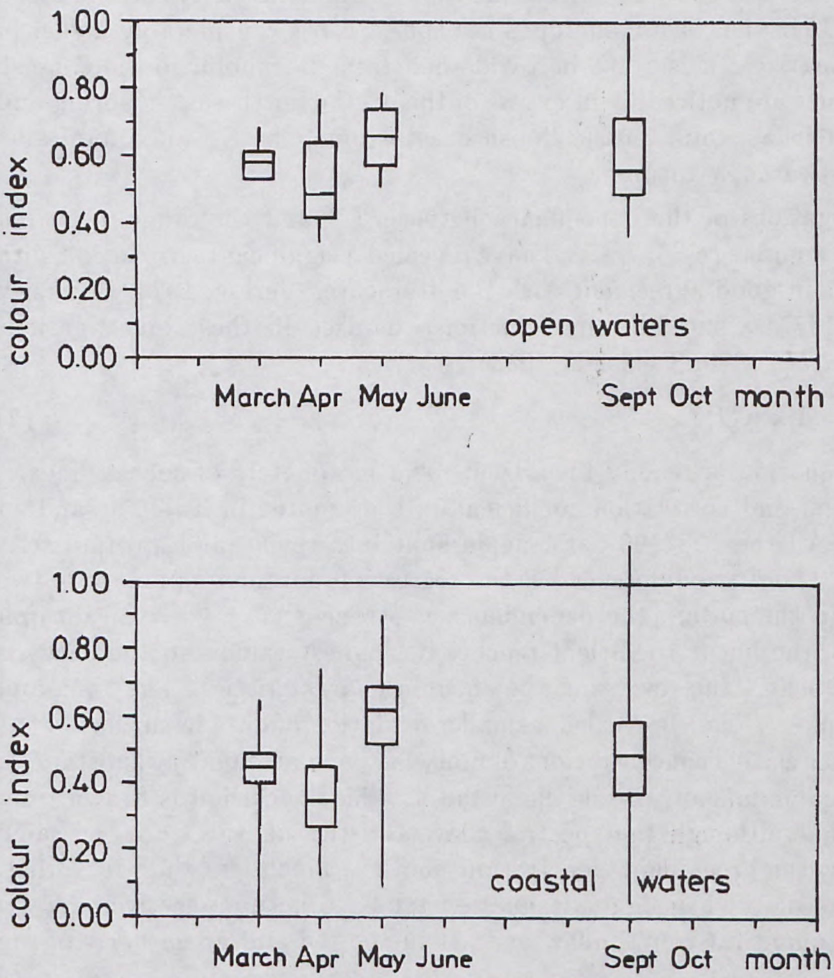


Fig. 6. 'Box and whiskers' analysis of temporal distribution of colour index

the shore. The 'box and whiskers' plot in Figure 6 clearly supports this statement. In addition, it reveals a similar statistical distribution of CI values in all months (height of boxes), with only slightly narrower distributions in early spring.

The distinct difference between the zones lies in the minimum and maximum values of CI, as well as in the presence of outliers. These values are much lower in the coastal zone. Minimum CI values occur in the coastal zone, due mainly to river input of organic and nonorganic substances. This conclusion is supported by the surface distribution of CI, which was averaged over the whole period of 1987–90 (Fig. 7). In both spring and autumn, the lowest values of CI (< 0.4) are observed in the Odra and Wisła river-mouth regions. In spring CI measurements show that the smaller rivers (in the Ustka and Łeba regions) are also carrying sediment loads.

The maps also show the above-mentioned difference between the mean values of CI in the coastal and open sea zones. CI is considerably higher in the open sea area: it is > 0.6 in a wide belt from Bornholm to the Gdańsk Deep. Values are noticeably in excess of this to the north-east in spring and to the east in autumn. In the Polish coastal zone, the CI maximum area moves westwards in autumn.

Investigations of the dependence between CI and the other measured optical parameters ($c(\lambda)$, K_d, Z_e) have revealed a significant correlation with Z_e. This is in good agreement with the literature, (Jerlov, 1974; Hojerslev *et. al.,* 1977). The following function was used in these investigations (Gordon *et al.*, 1980; Szekielda, 1988):

$$Z_e = A \times [CI]^B. \tag{2}$$

This equation is readily linearized. The parameters of such a linearized equation and correlation coefficients are presented in Table 3, and in Figure 8. All the 1987–90 data, again split into spring and autumn sets, was used. There are differences in the regression parameters for those two seasons. In the spring, the dependence is stronger (r = 0.87; in autumn r = 0.74), the linear coefficient reaches its highest value and the curve is negatively bent – the reverse of the autumn characteristics. The 'box and whiskers' plots (Fig. 8) revealed a smaller deviation of data in spring. What is more, the relative concentrations of nonselectively attenuating substances, like nonorganic matter, rise in the autumn. This conclusion is drawn from the fact that although the spectral characteristics of water are the same in autumn, the green-light penetration depth is much less than in spring. This occurs only when light attenuation tends to be nonselective, *i.e.* its effects are quantitatively similar, at least in the red and green parts of the spectrum.

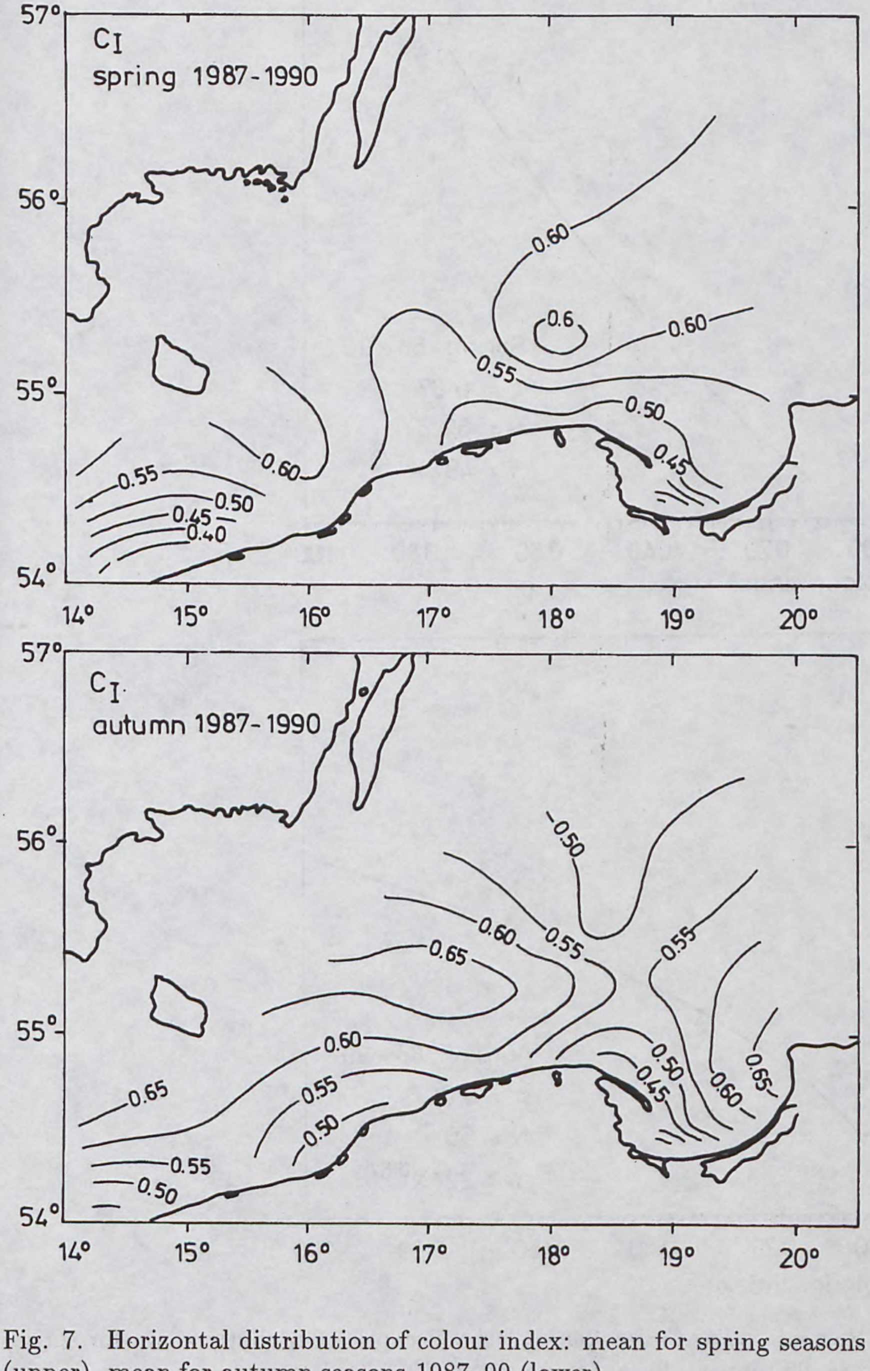
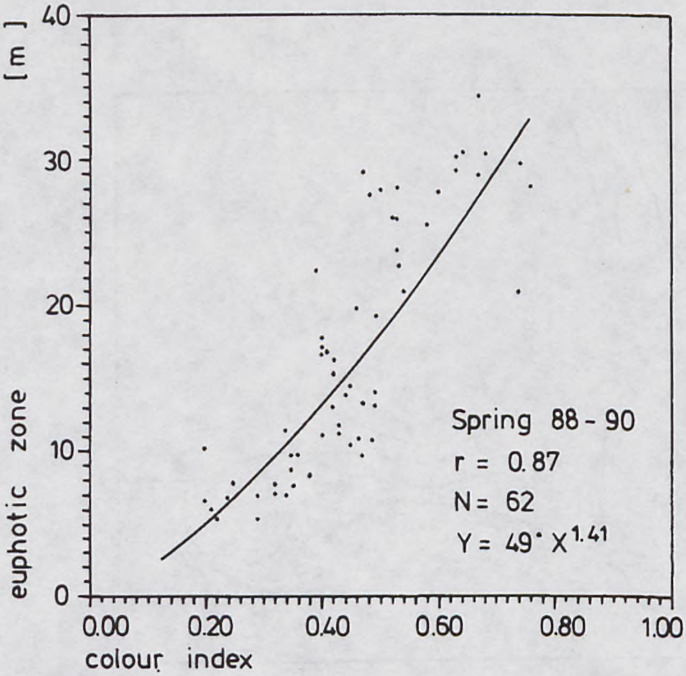


Fig. 7. Horizontal distribution of colour index: mean for spring seasons 1987–90 (upper), mean for autumn seasons 1987–90 (lower)



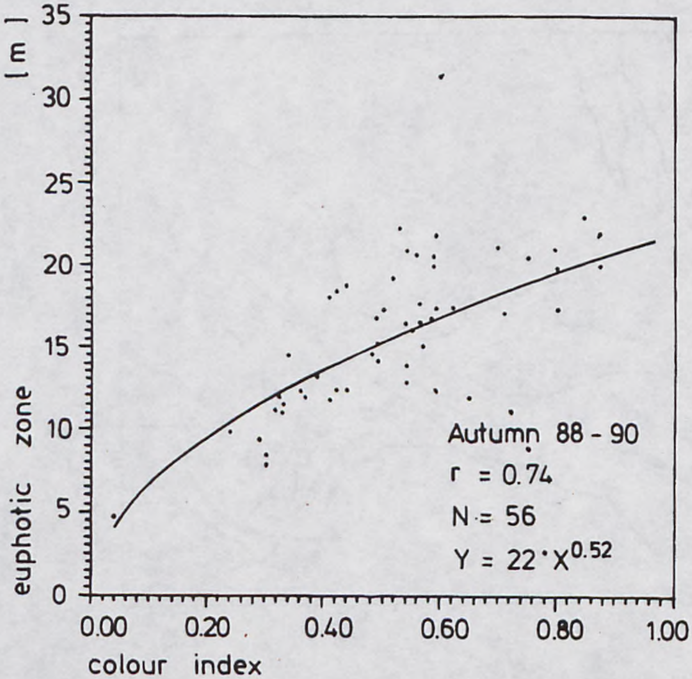


Fig. 8. Regression lines for colour index and depth of euphotic zone: for spring seasons 1988–90 (upper), for autumn seasons 1988–90 (lower)

4. Conclusion

The results presented here outline the optical characteristics of the investigated area. No clear tendencies were observed in the time-span analysed, except for a regular seasonal variability, especially in the deeper layers of the open sea.

A good local correlation between some of the parameters, *e.g.* between the attenuation coefficients in the blue, green and red parts of the spectrum, or between the colour index and the euphotic depth range, also seems to be an essential environmental characteristic of the region.

Optical properties of water, like light attenuation or colour index can assist in the correct interpretation of satellite images (*e.g.* surface chlorophyll *a* concentration (Sathyendranath and Platt, 1989)). The results presented here may lead to the investigated area being divided into several characteristic sectors, at least into open sea and coastal regions, with separation of bays and river mouths. Such a division could be further used to prepare separate remote sensing algorithms for these regions.

References

Dera J., 1983, *Marine physics,* PWN, Warszawa, (in Polish).

Gordon H. R., Clark D. K., Mueller J. L., Hovis W. A., 1980, *Phytoplankton pigments from the Nimbus-7 Coastal Zone Colour Scanner: comparison with surface measurements,* Science, 210, 63–66.

Hojerslev N. K., 1981, *The colour of the sea and its relation to surface chlorophyll and depth of euphotic zone,* Proc. EARSel-ESA Symposium, Voss, Norway, 19–20 May 1981.

Hojerslev N. K., Jerlov N. G., Kullenberg G., 1977, *Colour of the ocean as an indicator in photosynthetic studies,* J. Cons. Int. Explor. Mer., 37, 313–316.

Jerlov N. G., 1968, *Optical oceanography,* Elsevier, Amsterdam.

Jerlov N. G., 1974, *Significant relationships between optical properties of the sea,* Optical Aspects of Oceanography, Academic Press, New York, 77–94.

Jerlov N. G., 1976, *Marine optics,* Elsevier, Amsterdam.

Press W. H., Flannery B. P., Teuckosky S. A., Vetterling W. T., 1987, *Numerical recipes – the art of scientific computing*, Cambridge Univ. Press, Cambridge.

Sathyendranath S., Platt T., 1989, *Remote sensing of ocean chlorophyll: consequence of nonuniform pigment profile,* Appl. Opt., 28, 490.

Szekielda K. H., 1988, *Satellite monitoring of the Earth,* Wiley, New York.