Seasonal changes in selected optical parameters in the Pomeranian Bay in 1996–1997*

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Abstract

The main task of the Joint Polish-German Pomeranian Bay Project was to achieve a better understanding of the impact of freshwater discharge on this environment. The freshwater from the River Odra enters the Pomeranian Bay through four outlets. The most important of these is the River Świna, as it carries the largest volume of water exchange between the bay and the Szczecin Lagoon. This freshwater carries a large load of optically active substances: dissolved organic materials, mineral and organic sediments, as well as nutrients, which boost phytoplankton growth. The effect of riverine discharge can be traced with the use of optical methods. The elevated level of optically active components can significantly reduce the light required for photosynthesis. The Institute of Oceanology carried out a survey of selected inherent and apparent optical properties in the Pomeranian Bay in three seasons in 1996 and 1997. The results are presented and discussed, as are the relations between the various optical parameters and salinity.

* This work was carried out within the framework of a joint Polish-German research project in the Pomeranian Bay, sponsored by the Foundation for Polish-German Co-operation in Warsaw.

1. Introduction

The Pomeranian Bay is part of the southern Baltic, situated between the German islands of Rügen and Uznam (Usedom), the Polish island of Wolin and the Polish coast as far as Kołobrzeg. The maritime border of the Bay to the north is the line between Kap Arkona on Rügen and the Gąski lighthouse near Kołobrzeg. The maritime border of the bay to the west is the line between Peenemünde, the islet of Ruden and Kap Süd-Perd. In the north-west the Pomeranian Bay joins the Arkona Basin and in the north-east it merges with the Bornholm Basin. These Basins are separated from the bay by long, shallow interconnecting sandbars: the Eagle Bank, Odra Bank and Rönne Bank. The total area of the Pomeranian Bay is nearly 6000 km^2; it has a volume of 73 km^3 and a mean depth of 13 m (Majewski 1974).

The drainage area of the Pomeranian Bay consists of the drainage area of the Szczecin Lagoon (89.5%) and that of smaller rivers flowing directly into the sea: the Peene, Uecker and Randow on the German side of the Bay, and the Rega and Parsęta on the Polish side. The River Odra (Oder) and its tributaries make up 86.3% of the whole drainage area, so this river is the main source of freshwater to the Bay. Majewski (1974) calculated the 10-year-mean total outflow of freshwater from the drainage area between 1951 and 1960 at 17.6 km^3 per year. The riverine outflow peaks between January and April. That from the Szczecin Lagoon is very variable and depends on the interrelations between wind direction and sea level: inflows of saline water into the Lagoon alternate with outflows of freshwater pulses to the Bay (Robakiewicz 1993).

Freshwater discharges contain substantial loads of nutrients, as well as suspended and dissolved organic and inorganic materials. These plumes have a great impact on the annual cycle of environmental conditions in the Pomeranian Bay. High concentrations of suspended matter and dissolved organic substances (yellow substance) decrease water transparency and alter the conditions for photosynthesis.

The general aim of the joint Polish-German research project in the Pomeranian Bay, sponsored by the Foundation for Polish-German Co-operation was to achieve a better understanding of the impact of freshwater discharge to the study area. The task of the research team from Marine Physics Department of the Institute of Oceanology PAS was to gain a better knowledge of the local variability in the influx and transfer of solar energy to the Pomeranian Bay. The measurements of optical parameters included the registration of incident solar energy, its propagation across the sea surface and within the water. The underwater light field depends on the inherent properties of the water body, so the set of these parameters was also recorded: water transparency at $\lambda = 660\,\mathrm{nm}$, as well as the fluorescence profiles, chlorophyll *a* content and yellow substance absorption. The spectral reflectance was measured to establish an empirical relationship between optically active admixtures of seawater and the radiation emitted by this water. STD casting was performed during all cruises to establish a hydrological background for the optical phenomena.

As the main source of freshwater entering the Pomeranian Bay is the River Świna, the main sampling grid was centred in the river mouth in

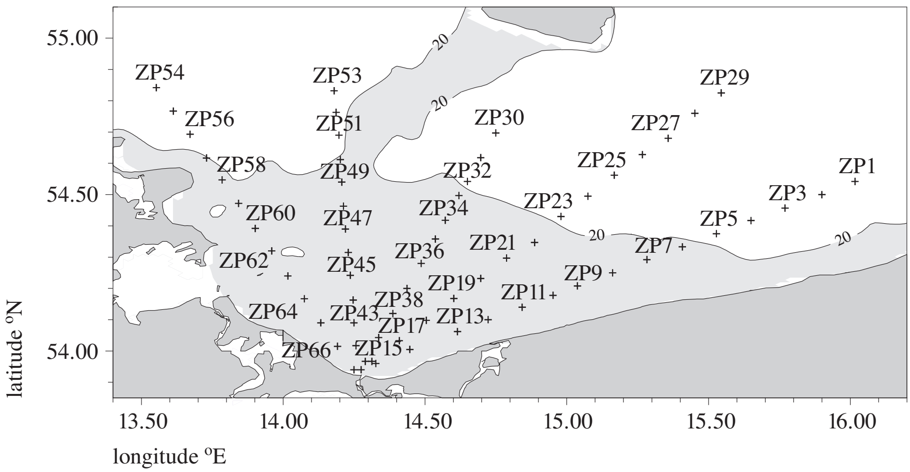


Fig. 1. The main grid of the sampling stations during research in the Pomeranian Bay in 1996–1997. The shaded area indicates depths from 0 to 20 metres

Table 1. List of research cruises and parameters measured

Cruise dates	Attenuation coefficient $c(660\,\mathrm{nm})$	Fluorescence	Yellow substance absorption coefficient $a_y(400\,\mathrm{nm})$	Remote sensing reflectance $R_{rs}(\lambda)$	Chlorophyll *a* C_a concentration	Diffuse attenuation coefficient $K_d\,(\lambda)$
March 1996	+	+	+	+	−	+
May 1996	+	+	+	+	+	+
September 1996	−	−	+	+	+	+
March 1997	+	+	+	+	+	+
April 1997	+	+	+	−	+	+
August 1997	+	+	−	−	−	+
September 1997	+	+	+	+	+	+
November 1997	+	+	+	−	−	+

Świnoujście Harbour and took the form of five 'rays' (see Fig. 1). This area was sampled during 8 cruises of the r/v 'Oceania' in 1996 and 1997. The western part of the experimental area belongs to Germany; experimental work was conducted there only in September 1996, and in April, August, September and November 1997. The list of optical parameters measured during the various cruises is given in Table 1.

2. Methods

Light beam attenuation $c(660)$ and fluorescence were measured *in situ* using an integrated optical profiler consisting of a transmissometer, fluorimeter and temperature sensor. The transmissometer operates with a modulated red light source (500 Hz, Siemens CQV30 660 nm diode). The instrument was air-calibrated (Højerslev & Lundgren 1977). Checking the instrument readings in distilled water showed it to be accurate to within 1% of the value for clear water (Smith & Baker 1981). A source of potential errors in *in situ* measurements is forward scattering due to the presence of particles. The error calculated for the average volume scattering function in Baltic water (Jonasz 1983) is 4%, which gives an overall measurement error of 5% for 1–4 m^{-1}, *i.e.* for typical $c(660)$ values in Baltic waters (Sagan 1991).

Fluorescence was measured with an adapted *Q Instrument ApS* (Hundahl & Holck 1980). The stimulating light is produced by a Xenon strobe discharge lamp fitted with an optical filter of 150 nm half-width, centred at 460 nm. Received light is sensed by a PIN photodiode after long-wave pass filtering (Shott & Genossen filter) with the edge at 665 nm. No calibration was made against chlorophyll contents.

Water samples were collected with Nansen bottles from various depths. Samples for the determination of the yellow substance absorption coefficient $a_y(\lambda)$ were processed exactly in accordance with the procedure recommended by Reuter *et al.* (1986) modified by Kowalczuk & Kaczmarek (1996) for application in Baltic Sea waters. The transparency of the samples was measured in the laboratory with the use of Perkin-Elmer Lambda 4 and Specord double-beam spectrophotometers in a 10 cm quartz cell in the 300–700 nm spectral range. A 10 cm quartz cell filled with doubly distilled water was used as reference. The transparency was then transformed into $a_y(\lambda)$. The accuracy of measurements was found from the reproducibility of a blank sample, with both optical cells filled with doubly distilled water. The small differences found in the spectra obtained correspond to a detection level for $a_y(\lambda)$ of 0.023 m^{-1}. The slope coefficients (S) of the yellow substance absorption spectrum were calculated by applying least-square methods to estimate the linear parameters of the spectrum on the semi-log scale in the 350–600 nm spectral range. The residual scattering effect was removed by subtracting the scattering component from the spectrum. By averaging $a_y(\lambda)$ in the spectral range 650–700 nm, where the linear model was not fulfilled, this component could be assessed. The mean value of the absorption coefficient was then subtracted from the whole spectrum.

Water samples for chlorophyll *a* content (C_a) were taken from the same probe as for yellow substance and then filtered on board with the use of Sartorius GF/F filters (pore size 0.45 mm). The methanol extraction method and the Jeffrey & Humphrey (1975) formula were applied to calculate the pigment concentration.

Measurements of the remote sensing reflectance $R_{rs}(\lambda, z^-)$ (Lee *et al.* 1997) were made using a MER2040 spectrophotometer (Biospherical Instruments Inc., USA) at ten spectral channels: 412, 443, 490, 510, 550, 589, 625, 665, 683, 710 nm. The measurement protocol was consistent with the reflectance measurement protocol for the SeaWiFS Project (Mueller & Austin 1992, 1995), including correction for self-shading (Gordon & Ding 1992, Zibordi & Ferrari 1995).

The diffuse attenuation coefficient $K_d(\lambda, z)$ was measured with a marine spectroradiometer constructed at the Institute of Oceanology PAS (Woźniak & Montwiłł 1973) in the following spectral bands: 400, 425, 465, 525, 535, 580, 620, 680 nm, altered in 1997 according to SeaWiFS specifications to 412, 443, 490, 510, 550, 625, 665 and 683 nm.

3. Results

The experimental data were analysed in terms of temporal and spatial variability. Within the data set the following subsets were created: shallow- (depth < 20 metres) and deep-water (depth > 20 metres) stations (see Fig. 1). The following seasonal subsets were suggested: spring (with the end of winter included if not specially denoted) for data collected in March, April and May; summer for data collected in August and early September; autumn for data collected in late September and November. The data were organised for analysis in this way because the water in the shallow and deep parts (Arkona and Bornholm Basins) of the Pomeranian Bay has different properties.

3.1. Inherent optical properties

The difference in the optical properties of the shallow and deep parts of the Pomeranian Bay is clearly visible on the seasonally-averaged depth profiles of the beam attenuation coefficient at $\lambda = 660$ nm and fluorescence (Figs. 2 and 3). The water in the Arkona and Bornholm Basins is more transparent and has a lower fluorescence than the shallow part of the bay

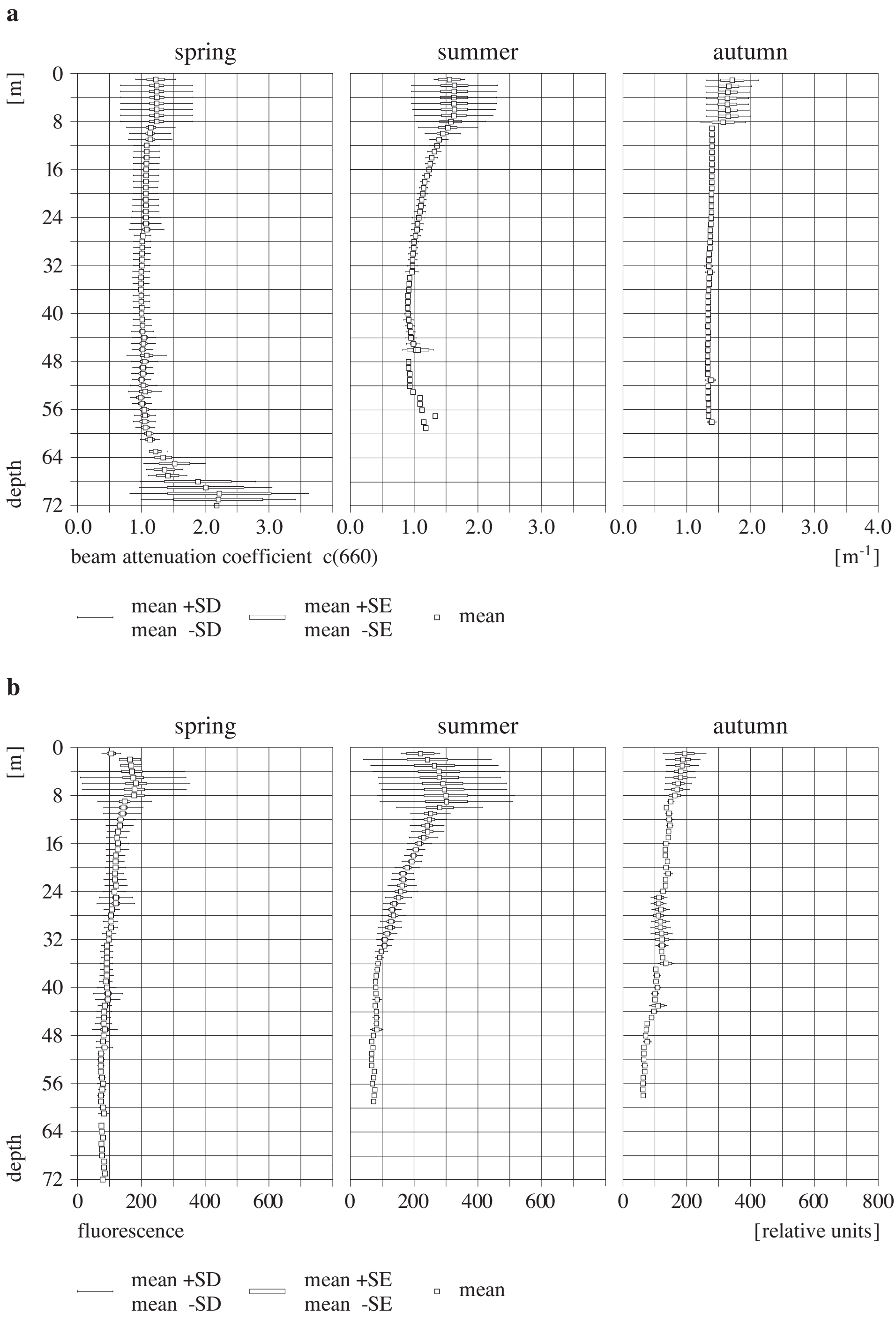


Fig. 2. Seasonally averaged depth profiles of $c(660)$ (a) and fluorescence (b) at deep-water stations

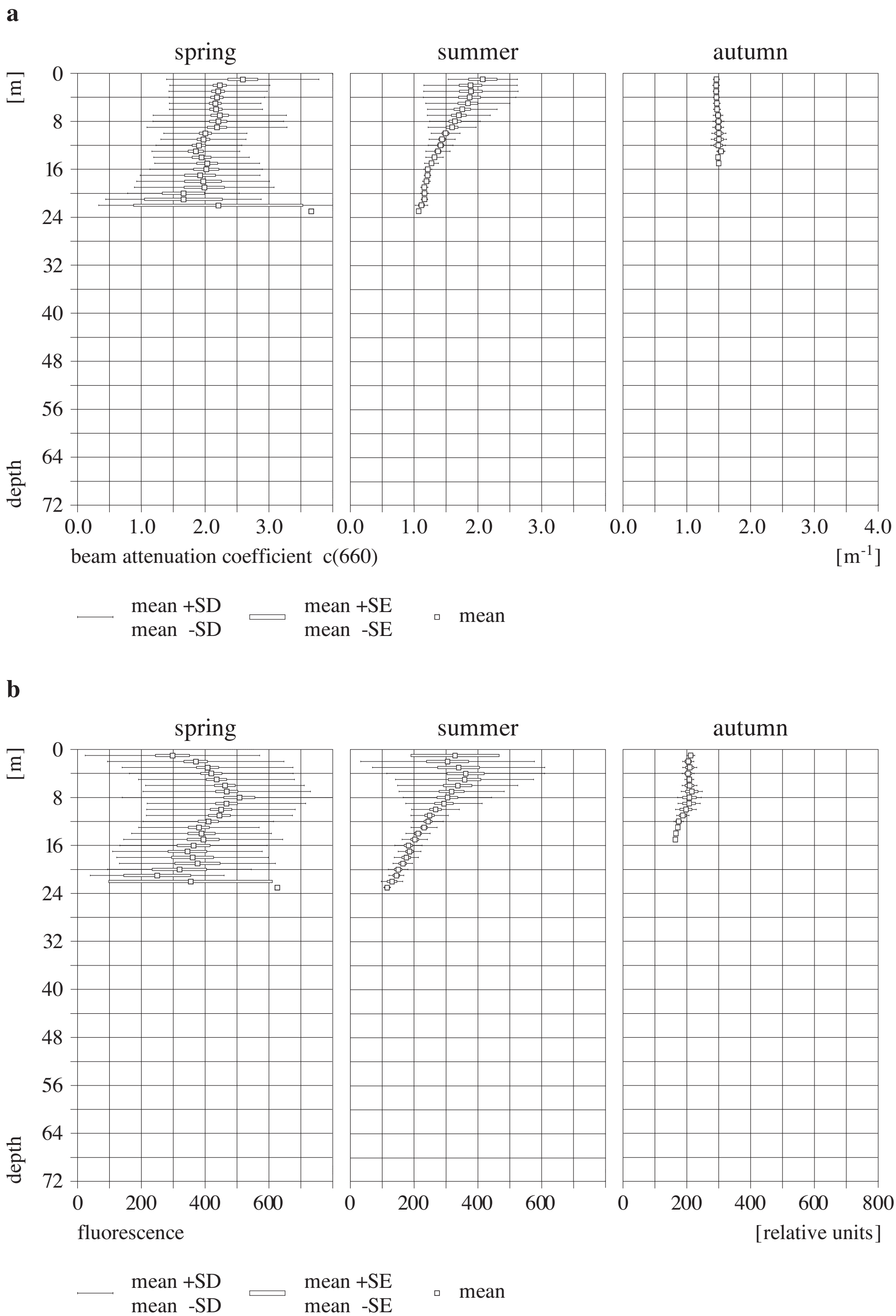
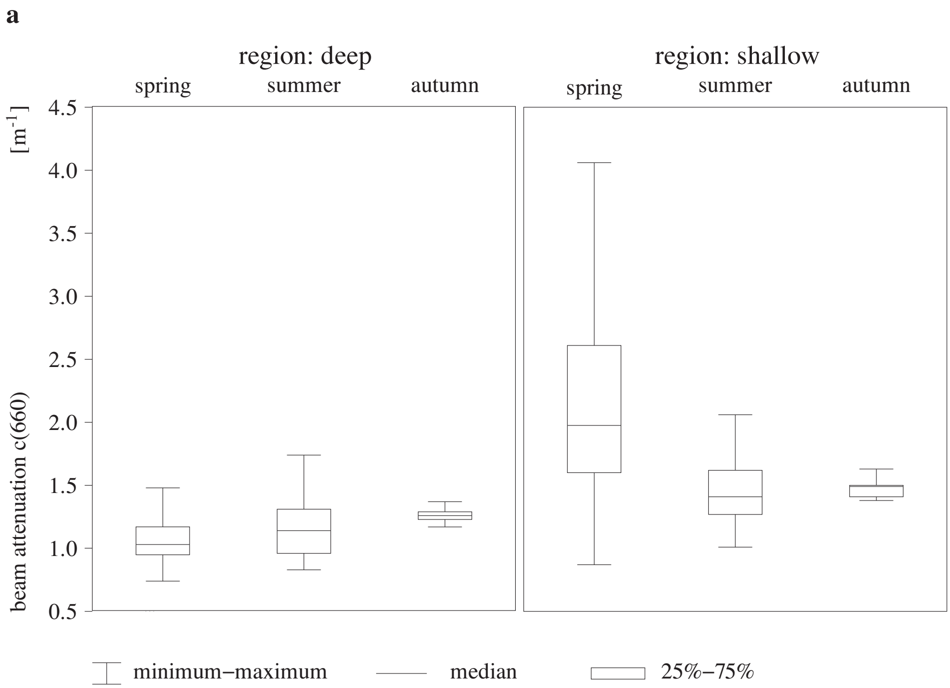


Fig. 3. Seasonally averaged depth profiles $c(660)$ (a) and fluorescence (b) at shallow-water stations

in spring and summer, but in autumn these parameters are almost the same. The averaged depth profile of the attenuation coefficient is similar at the deep-water stations in all seasons. There is a small increase in $c(660)$ in the surface layer down to a depth of 12 metres in the various seasons. The summer $c(660)$ profile follows the summer fluorescence profile almost exactly, with a clearly visible subsurface chlorophyll maximum. This suggests that the algal bloom associated with the flood water outflow played a dominant part in forming the transparency regime during August and early September 1997. The transparency profile in the 25–50 metre depth range is smooth and fluctuates around $1\,\mathrm{m}^{-1}$, except in autumn when the depth-averaged $c(660)$ is $>$ *ca* $1.25\,\mathrm{m}^{-1}$. Another interesting feature of the depth profile of the deep-water stations is the increase in $c(660)$ near the bottom in spring. Unfortunately, no such data are available for other seasons. This is the effect of re-suspension of mineral particles caused by a near-bottom current of saline water from the North Sea, which submerges in the depths of the Bornholm Basin during winter inflow events. The shape of the spring fluorescence profile confirms the correctness of our interpretation. Moreover, the profile displays no obvious increase in $c(660)$ in the same depth interval.

The averaged depth profiles of the beam attenuation coefficient and fluorescence in shallow water are generally much more variable than those of the deep-water stations; in autumn, however, this was not found to be the case, perhaps because of the small sample size. The depth-averaged values of $c(660)$ and fluorescence are much larger than in the open part of the Pomeranian Bay. The influence of the Świna is evident, because most of the shallow-water stations are located near the river's mouth. The presence of fresh riverine water, which carries a large load of suspended matter and organic material, causes the turbidity and fluorescence to increase. However, the pulsating, irregular inflow of the freshwater means that both these parameters are highly variable, hence the high standard deviation. The average $c(660)$ in spring and autumn is equally distributed by depth and shows a wide range of variability. This is the effect of intensive vertical mixing as a result of the typical seasonal decrease in thermal stratification and strong wind stress due to westerly storms. It should be noted that the spring florescence profile displays a significant subsurface chlorophyll maximum. A similar feature can be seen on the summer depth distribution profiles of $c(660)$ and fluorescence.

Figure 4 illustrates the statistical distribution of the beam attenuation coefficient and fluorescence at deep- and shallow-water stations in the respective seasons. The plots reveal significant differences in optical properties between the outer and inner parts of the Pomeranian Bay. In the deep part



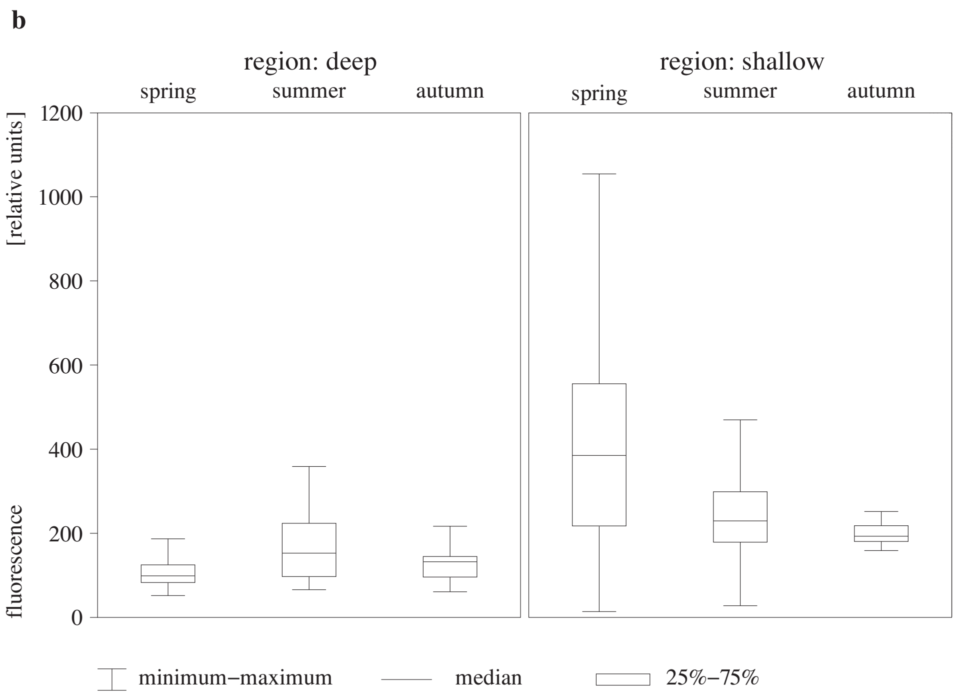


Fig. 4. Seasonal statistical distribution of values of $c(660)$ (a) and fluorescence (b) at deep- and shallow-water stations

of the bay, attenuation coefficients and fluorescence were lowest in spring, but much higher in summer. In autumn $c(660)$ reaches a maximum in open water, whereas fluorescence tends to decrease. This could be explained by the presence of a large number of dead phytoplankton cells in the water column, which effectively attenuate light but do not respond to excitation by blue light. The average values of $c(660)$ and fluorescence in shallow waters are distinctly higher (see Table 2) than at the deep-water stations. The values of both parameters reach a maximum in spring and a minimum in autumn. In shallow waters the pattern of increased attenuation and reduced fluorescence in autumn in comparison to summer is similar.

During five cruises – in March, May and September 1996 and March and August 1997 – measurements were carried out along a radius between the sampling points ZP17–ZP29, from the Świna towards the Bornholm Basin. The spatial distribution of $c(660)$ and fluorescence is typical of an estuarine environment. The sampling stations situated close to the river mouth, near the source of the freshwater carrying a large load of suspended matter, nutrients and dissolved organic matter, yield much higher readings of $c(660)$ and fluorescence than the waters of the Bornholm Basin. The depth profiles of both parameters plotted for specific cruises were similar in appearance. We have chosen as an example the profile recorded during the cruise in March 1996 (see Fig. 5), because it illustrates the increase in attenuation and fluorescence and also contains features not present in other plots. The depth profile shows the increase in $c(660)$ in the shallow part of the Pomeranian Bay. The waters of the Bornholm Basin are relatively clear. In the shallow part of the bay this parameter achieves a local maximum at around 10 m depth. This is the effect of phytoplankton concentration under favourable light conditions. Apart from this maximum, the depth distribution of the attenuation coefficient is quite uniform. This may be the effect of wind-induced mixing, which in shallow water reaches the bottom. Near the bottom of the Bornholm Basin a significant increase in attenuation was recorded, caused by re-suspension due to the near-bottom current. This current is associated with the annual winter intrusion of dense saline waters from the Danish Straits. The fluorescence depth profile reaches extremely high values in the shallow part of the bay. Near the surface, the fluorescence exceeds 900 [rel. units], which is the maximum recorded in the whole data set. Such high values could be associated with the annual phytoplankton bloom (most probably, diatoms were present). In open, deep waters the fluorescence dropped radically and was quite uniformly distributed with depth.

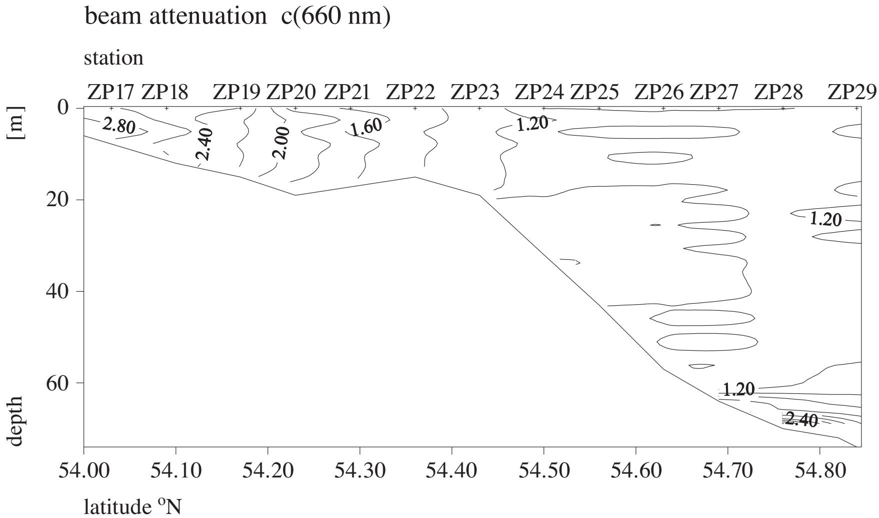
The seasonal distribution of the yellow substance absorption coefficient at $\lambda = 400\,\mathrm{nm}$, $a_y(400)$, and the yellow substance absorption spectrum

Table 2. Seasonal distribution of statistical values of the inherent optical properties in shallow and deep regions of the Pomeranian Bay in 1996–1997

	Shallow water region, depth < 20 m						Deep water region, depth ≥ 20 m					
	Spring		Summer		Autumn		Spring		Summer		Autumn	
	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
$c(660)$	2.13	0.87	1.55	0.50	1.48	0.07	1.10	0.34	1.20	0.38	1.31	0.18
fluore-scence	424	258	269	166	199	24	117	78	180	122	128	44
size	$n = 784$		$n = 290$		$n = 40$		$n = 1145$		$n = 377$		$n = 166$	
$a_y(400)$	0.66	0.26	0.87	0.43	1.12	0.31	0.53	0.17	0.70	0.11	0.76	0.03
slope S	0.022	0.005	0.021	0.005	0.017	0.002	0.022	0.006	0.020	0.004	0.016	–
size	$n = 51$		$n = 41$		$n = 6$		$n = 25$		$n = 20$		$n = 3$	

SD – standard deviation

a



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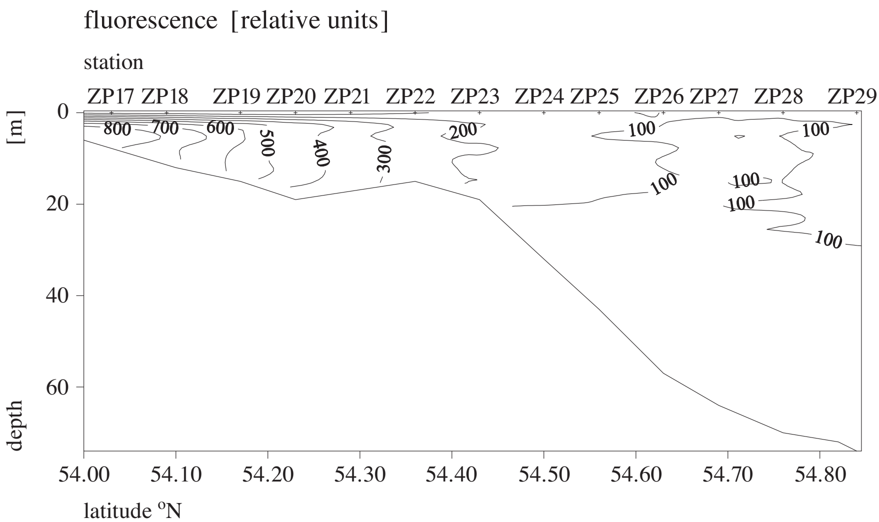


Fig. 5. Vertical distribution of $c(660)$ (a) and fluorescence (b) recorded during the cruise in the Pomeranian Bay along transect ZP17–ZP29 in March 1996

slope coefficient S is presented in Fig. 6 and Table 2. The distribution pattern of the median $a_y(400)$ in shallow and deep waters is similar, except for the ranges of the minimum and maximum values. The maximum yellow substance absorption in the shallow part of the Pomeranian Bay is twice as great in comparison with the deep part. The minimum $a_y(400)$ was recorded in spring. In summer, absorption increased significantly. Absorption in the shallow part was generally higher than in the

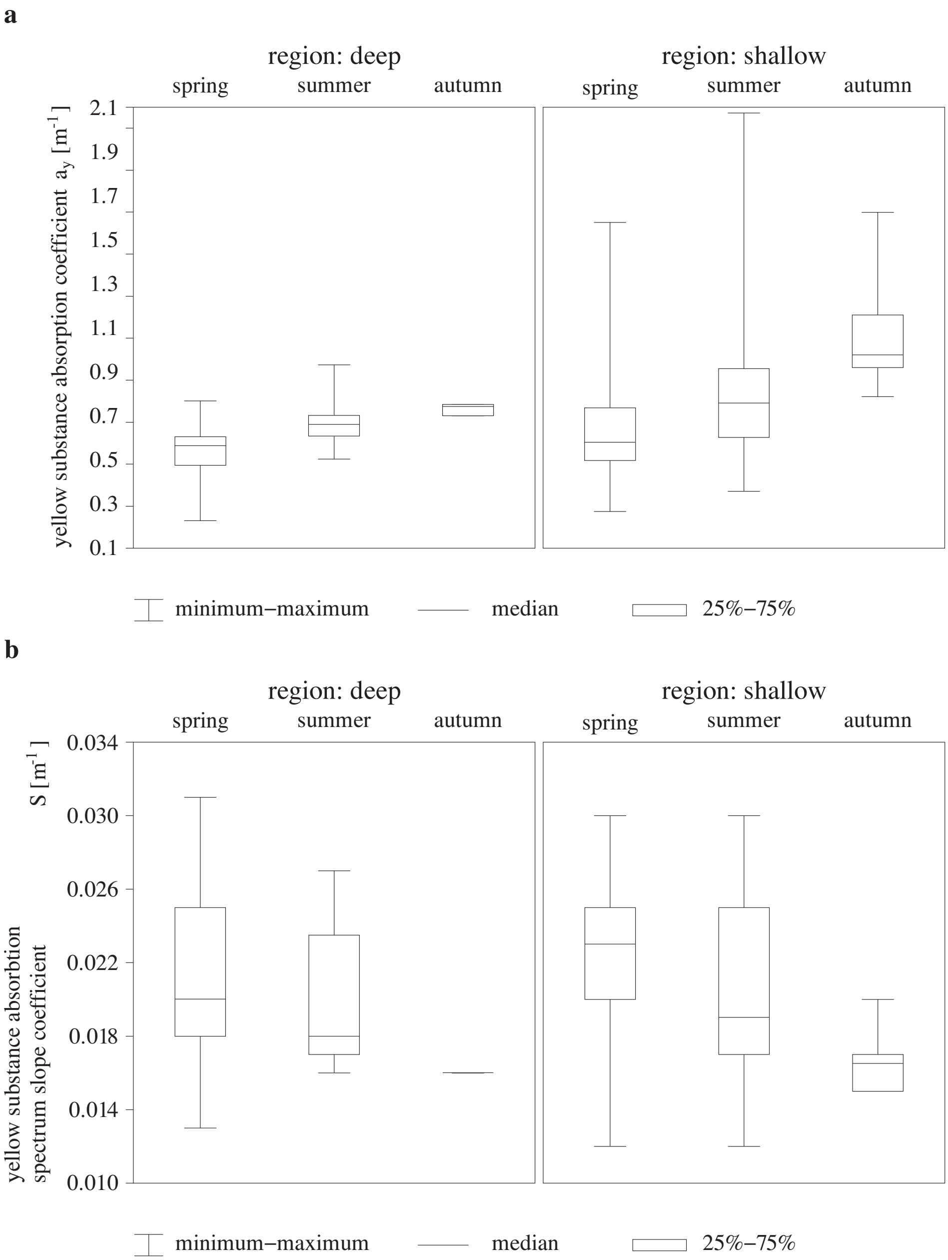


Fig. 6. Seasonal statistical distribution of $a_y(400)$ (a) and S (b) at deep- and shallow-water stations

deep-water. Very high absorption values in autumn are an artefact, because the calculations were done on a data set collected during a single cruise in November 1997. During that cruise, the water samples were taken in the riverine water plume, which at that time was concentrated in the western part of the sampling grid in the German part of the bay.

Figure 6a shows the statistical distribution of the slope coefficient of the yellow substance absorption spectrum. The range of variability of S is typical of an area affected by freshwater outflow. The low values of this parameter are associated with freshwater. This usually carries more humic acids, which have flatter absorption spectra. In seawater the fulvic fraction of humus prevails, so the spectra are steeper. The averaged low absorption is associated with a steep spectrum, the averaged high absorption with a flatter spectrum (correlation coefficient $r = 0.61$, sample size $n = 146$). This phenomenon is related to the various chemical and physical processes which yellow substance undergoes in the transition zone between the fresh- and salt-water environments, and to the chemical properties of the freshwater humus in the drainage area. A detailed discussion of this topic can be found in Kowalczuk (in press), but it should be emphasised that there has never yet been such good correspondence between absorption and the slope coefficient in Polish coastal waters.

Samples for yellow substance absorption were collected only at the surface. The regular sampling grid and the relatively short measurement time during the cruises was favourable for the calculation of the quasi-synoptic horizontal distribution of this parameter (the Kriging method with the exponential semivariogram model). The maps plotted show a similar qualitative pattern (see Fig. 7.): a significant increase in $a_y(400)$ near the Świna and Dziwna and a uniform distribution in the open sea. An interesting feature was discovered: a lens of poorly-absorbing water over the Odra Bank (May and September 1996, April 1997, Figs. 7b,c,e). The range of the increased absorption field is not big and depends on the riverine plume movements controlled by wind and density conditions. With the prevailing wind directions from W, SW and ENE (around 60% – Majewski 1974), the riverine plume tends to concentrate along the Polish (W winds, Fig. 7e) or the German (E winds, Fig. 7f) coasts. Quite an unusual situation was recorded in late August and early September 1997. By that time most of the flood water had spread throughout the whole western part of the Pomeranian Bay. The high volume of freshwater entering the bay raised the absorption of light by yellow substance in that part of the region. This observation was corroborated by satellite observation of yellow substance absorption by Siegel *et al.* (1998).

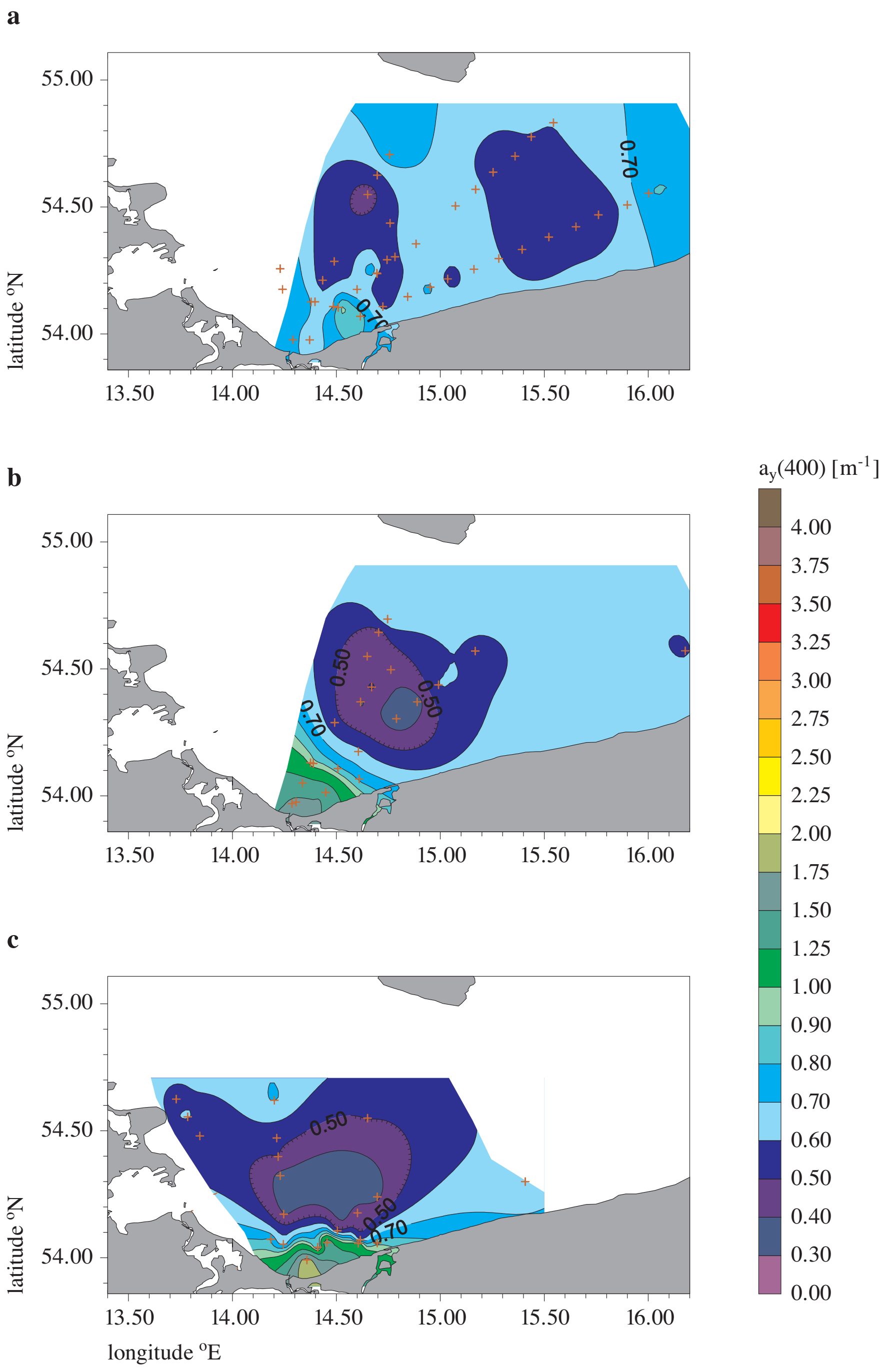


Fig. 7. Spatial distribution of $a_y(400)$ [m^{-1}] in the Pomeranian Bay measured during the following cruises: March 1996 (a), May 1996 (b), September 1996 (c), March 1997 (d), April 1997 (e), and August–September 1997 (f)

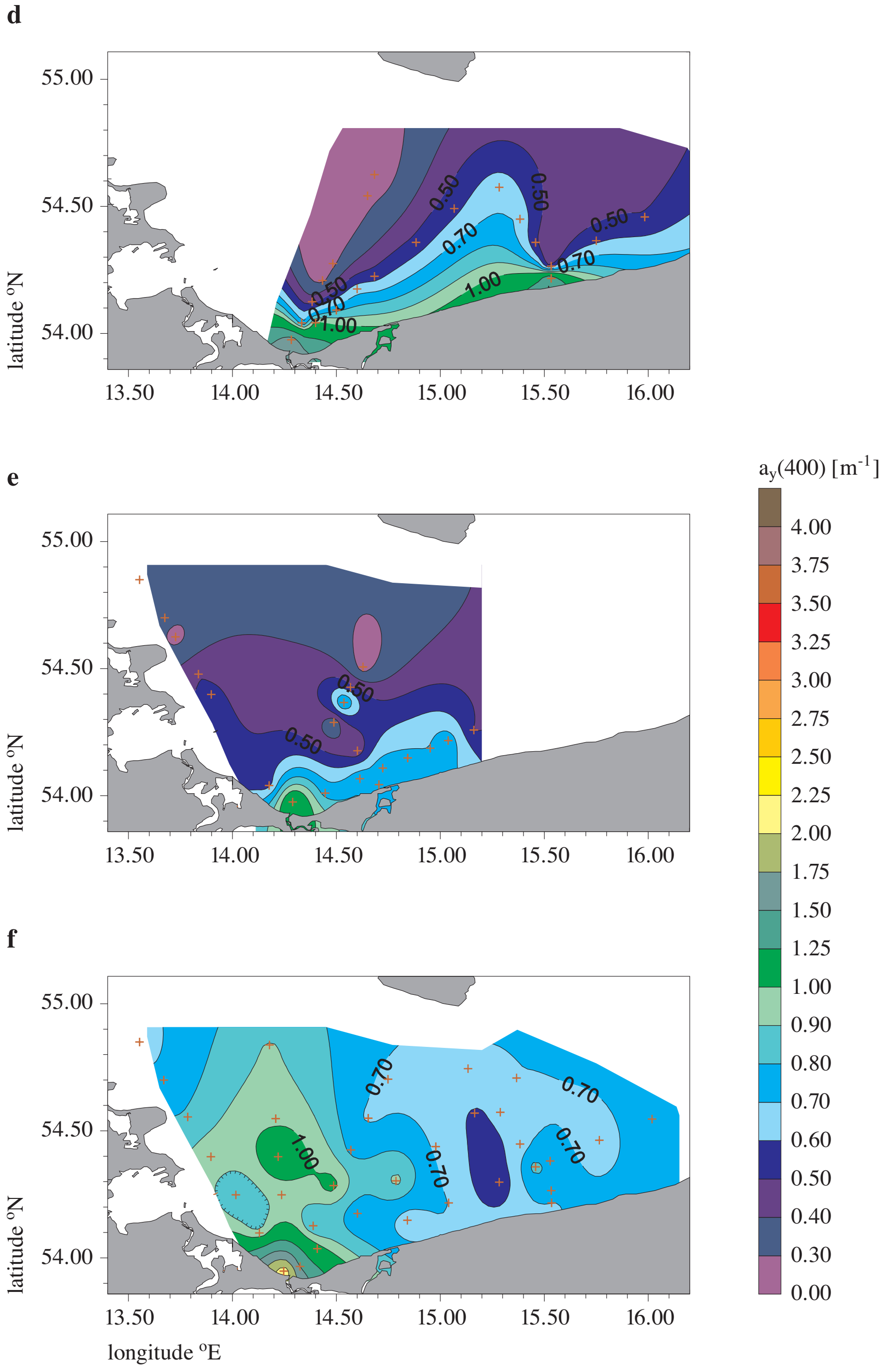


Fig. 7. (continued)

3.2. Apparent optical properties

Two apparent optical parameters were measured during the experiment in the Pomeranian Bay: the spectrum of the remote sensing reflectance R_{rs} and the spectrum of the diffuse attenuation coefficient K_d. The former enabled a local in-water remote sensing algorithm to be constructed to determine the chlorophyll content C_a and yellow substance absorption coefficient $a_{ys}(400)$ (Olszewski *et al.* 1999). The latter enables the depth of the euphotic zone in the Photosynthetic Available Radiation (PAR) spectral range or in specific spectral bands to be calculated. Thus, the light conditions for algal growth can be estimated. This parameter is also used in the equations for calculating primary production.

Figure 8 shows seasonal changes in the remote sensing reflectance spectrum. As the reflectance was measured in surface water, we did not divide the data into shallow- and deep-water subsets. There is little difference between the seasonally averaged spectra at the end of winter and in summer; the latter displays slightly lower values in its red part. It should be noted here, though, that the reflectance spectrum is characteristic of the integral type, *i.e.* each of its points is due to the overall effect of light interaction with all the seawater components. The slight differences in the

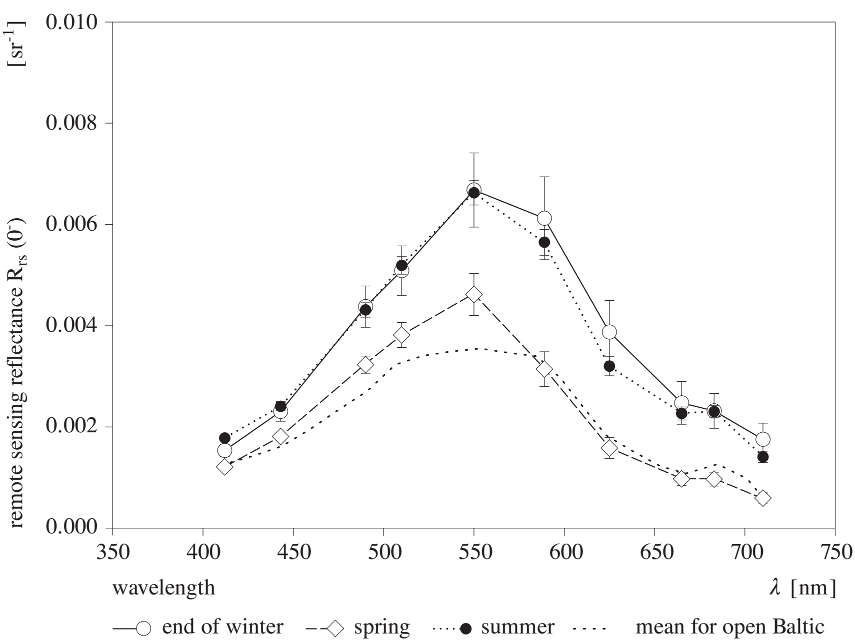


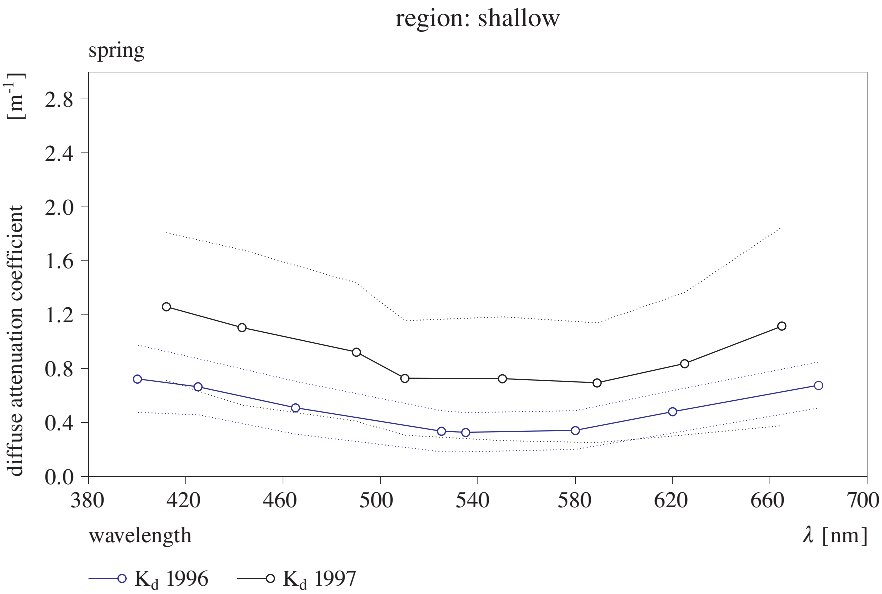
Fig. 8. Spectra of the remote sensing reflectance measured during the Pomeranian Bay experiment and seasonally averaged

spectrum shape may therefore have been caused by quite large differences in the marine water composition. Generally speaking, the high spectral reflectance is due to strong but poorly selective backscattering by suspended matter, or to low, more selective absorption by all the optically important constituents of water. Except for the red waveband in spring, all the seasonal reflectance spectra in Fig. 8 have high values, mostly much greater than those for the open sea given in Olszewski *et al.* (1999). The significantly lower values of the reflectance spectrum in spring, compared to the end of winter, seems to be the effect of increased light absorption by phytoplankton during its spring bloom rather than the effect of decreased scattering by suspended matter. The repeated greater reflectance along the full spectral range in summer is possibly the effect of increased scattering by suspensions in the freshwater plume from the summer flood in the Odra drainage area in 1997.

Spectra of the diffuse attenuation coefficient are plotted in Fig. 9. There are very large differences between the shallow and deep regions in the respective seasons: K_d spectra in shallow waters are much higher than those in the deep-water region. There are also differences in the spectra measured in the various seasons in 1996 and 1997. The spring 1996 spectra take much lower values in all wavebands than those measured in 1997. The maximum transmittance wavelength is usually located in the green spectral band, except in the shallow part of the bay in spring 1997, when it shifted to the yellow part of the spectrum.

K_d spectra in summer take higher values than in spring for both regions and years. Moreover, in this season there is a clear difference between 1996 and 1997. The summer 1997 spectra clearly demonstrate the influence of the floodwater on the transmission of light into the sea. In comparison with the 1996 spectra, the blue part of the K_d spectrum exhibits extreme values. The slope of the 1997 spectra is much bigger than the 1996 one and the maximum transmittance wavelength shifted from the green in 1996 to the yellow band in 1997. The high K_d values in the blue and green parts of the spectrum, as well as the shape of the spectrum, are caused by the large load of yellow substance transported with the flood. The impact of the increased absorption of blue light by yellow substance on K_d can also be seen in the spectrum measured in the deep, open part of the bay in summer 1997. K_d spectra recorded in this area in 1996 and 1997 are very similar in the green and red bands, with a similar position of the maximum transmittance in the green spectral band. The only difference is in the blue light: the 1997 spectra have higher values and are much steeper in this spectral region than the 1996 spectra.

a



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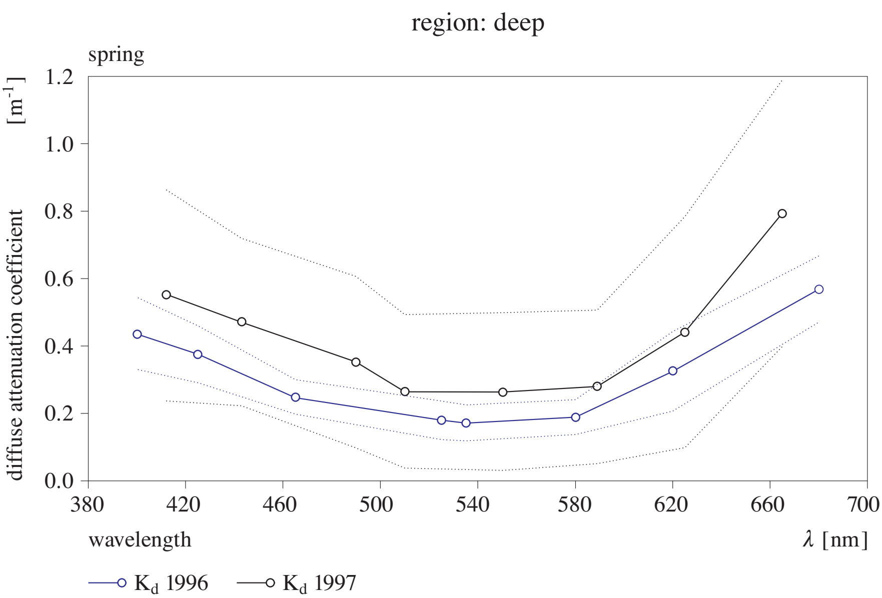

Fig. 9. Averaged spectra of the diffuse attenuation coefficient measured during the Pomeranian Bay experiment in selected seasons and regions (a–d). Dotted lines indicate the standard deviation of the spectra

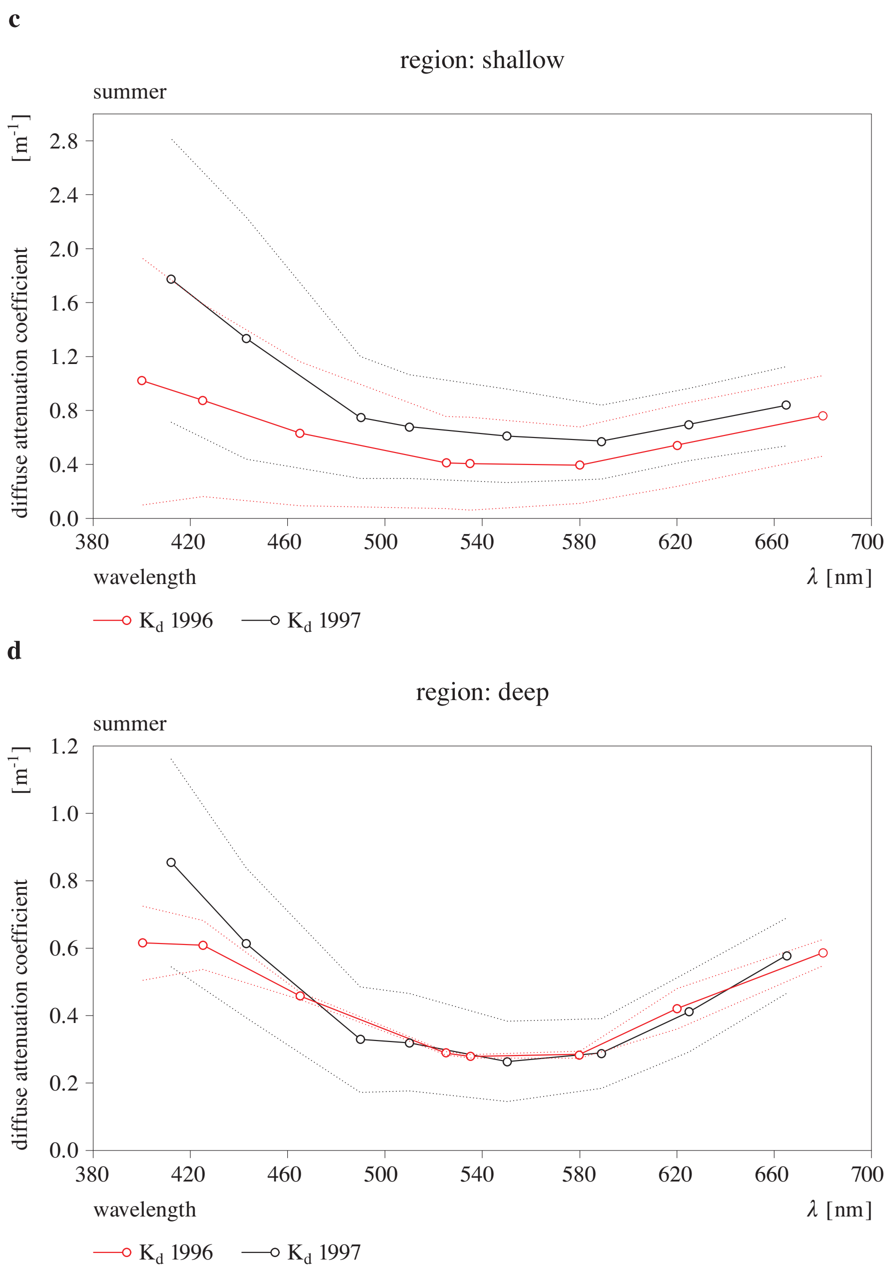

Fig. 9. (continued)

The spectral distribution of K_d was used to calculate the depth of the euphotic zone. This parameter gives the depth to which 1% of surface irradiance can reach in the spectral band of maximum transmission (centred at 535 nm). An example of the changes in this parameter as a function of distance from the mouth of the Świna is shown in Fig. 10. These measurements were made on 31 August – 4 September 1997, while the flood wave was entering the Pomeranian Bay. The riverine plume concentrated along the German coast of the bay and a reduced depth of the euphotic zone along the ZP66–ZP56 transect was noted up to 78 km from the river mouth. The changes in this parameter along the central ZP40–ZP32 transect were much larger but the range of riverine discharge was much smaller at about 40 km.

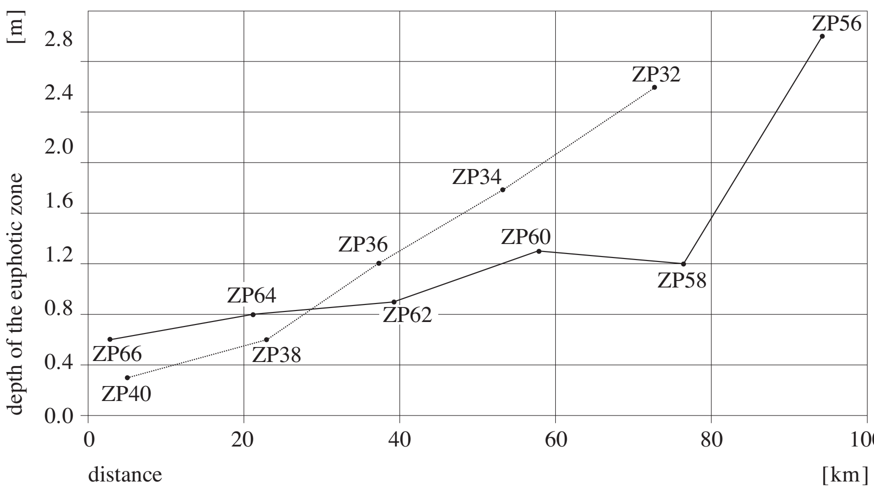

Fig. 10. Changes in the depth of the euphotic zone along two transects in the Pomeranian Bay measured in August 1997

4. Discussion

The freshwater runoff from the Odra drainage area has an impact on the statistical and spatial distribution of the values of the optical parameters discussed in this paper. It is essential for further discussion to describe the hydrological regime of this river in 1996 and 1997. Under average conditions (1951–1960) the flow in the Odra is greatest (46%) in the first four months of the year, with the maximum in March 13.3% (Majewski 1974). In hydrological terms, the two years of our experiment were unusual. The winter of 1995–1996 was one of the most severe of the decade, and ice conditions were very bad. Ice first began to form in December 1995, and the last remnants were still present in early April 1996. On 21–22 February 1996 the Bay was covered with thick ice to a distance of 6 nautical miles offshore, and even large ships had problems getting through

(Sztobryn & Stanisławczyk 1997). Under such circumstances, runoff of suspended matter and yellow substance was much reduced since the soil was frozen. However, in March 1996, when the ice cover started to melt, the suspended matter, nutrients and dissolved organic matter, all of which had been preserved in the ice, were now released and triggered an extensive bloom of diatoms. That year the Odra runoff peaked in April, May and June (Niemirycz & Borkowski 1997). In the following year the usual spring maximum in the Odra flow did not occur. The flow was approximately even throughout the year, with the exception of July and August. In summer 1997 a catastrophic flood occurred in the Odra and Wisła catchment areas in Poland and the Czech Republic. During those two months, the Odra's flow-rate rose more than sixfold, from $500\,\mathrm{m}^3\,\mathrm{s}^{-1}$ to $3200\,\mathrm{m}^3\,\mathrm{s}^{-1}$ (Heybowicz *et al.* 1998). Those two climatic phenomena had a great impact on optical conditions in the Pomeranian Bay. Therefore, all ranges of variability of most of the parameters measured should be regarded as extremes; they do not describe average conditions.

Statistical analysis of the relation between optical properties and environmental parameters like temperature and salinity has demonstrated that only $a_y(400)$ and K_d are correlated with salinity (a_y *vs.* salinity: $r = -0.74$, $n = 80$ and $K_d(412)$ *vs.* salinity: $r = -0.66$, $n = 35$). In the case of $c(660)$ and fluorescence this relation is much weaker. The $a_y(400)$ coefficient is well correlated with the diffuse attenuation coefficient in the blue light (a_y *vs.* $K_d(400)$: $r = 0.76$, $n = 21$ and a_y *vs.* $K_d(412)$: $r = 0.58$, $n = 26$). The K_d coefficient is a measure of total absorption, and the mean relative proportion of the absorption of light by yellow substance in the total absorption is 62% in the bay waters of the southern Baltic (Kowalczuk & Darecki 1998). Therefore one can justifiably assume that $a_y(400)$ is an indicator of the freshwater plume.

The level of $a_y(400)$ is connected with the amount of dissolved organic matter transported to the Pomeranian Bay by rivers. The hydrological regime of the Odra during this experiment had a great impact on this parameter. The hard winter in 1995–1996 stopped the supply of the Bay with yellow substance. Therefore, the mean values of this parameter in the shallow and deep parts of the bay were close to the five-year-average value of $a_y(400)$ in the open water of the southern Baltic in winter (Kowalczuk, in press). The mean summer values of this parameter in the shallow and deep regions were smaller than the respective five-year-average values in the bay and open waters quoted in Kowalczuk (in press). This may be the effect of the Szczecin Lagoon. Acting as a buffer, this is where many chemical and physical processes of yellow substance degradation take place. The amount of organic matter entering the sea from the Lagoon is smaller in comparison with the Gulf of Gdańsk. It should be noted, however, that light absorption by yellow substance recorded in the freshwater plumes in the Pomeranian Bay is contained within the entire variability range of this parameter characteristic of Baltic bay waters. Similar values of $a_y(400)$ in this region were given by Siegel *et al.* (1997).

The spatial distribution of the yellow substance absorption field is determined by the drift of the freshwater lens. The paper by Beszczyńska-Möller (1999) presents typical freshwater distribution patterns in the Pomeranian Bay, which depend mostly on wind conditions. During the Pomeranian Bay experiment the optical and hydrographic measurements were performed simultaneously. There is good correspondence between the salinity distribution and increased $a_y(400)$ in two situations: in April 1996, when the freshwater plume with a salinity < 7 PSU spread eastwards along the Polish coast, and in August 1997, when flood water plumes drifted along the German coast. The graphs illustrating the surface distribution of $a_y(400)$ show increased absorption in the same locations. Krawczyk *et al.* (1997) and Siegel *et al.* (1998) also reported the $a_y(400)$ spatial distribution on satellite imagery in 1996 and 1997.

As has already been mentioned, the beam attenuation coefficient and fluorescence are poorly correlated with salinity, but both parameters are well correlated with each other and with the chlorophyll *a* concentration ($c(660)$ *vs.* fluorescence: $r = 0.80$, $n = 2802$; $c(660)$ *vs.* C_a: $r = 0.68$, $n = 71$; fluorescence *vs.* C_a: $r = 0.75$, $n = 71$). This suggests that the biological activity of algae is responsible for the variability in both parameters. The seasonal changes display the typical high values of $c(660)$ during spring, especially in shallow, offshore areas. This is due both to the high concentration of suspended material carried by the Odra and the intensive phytoplankton growth visible as a high fluorescence signal observed at the same time. The maximum and minimum $c(660)$ values vary in their order of magnitude (Fig. 4). Towards autumn, as the biological activity decreases, the water becomes more transparent. Furthermore, $c(660)$ becomes more concentrated around its mean (Table 2) with no extremes.

Spatially, the bottom topography and the offshore distance govern the optical properties of the Pomeranian Bay. Shallow waters are optically uniform from surface to bottom, especially during spring, because of the heavy load from the land, and in autumn, due to intensive wave-induced mixing. Deep-water optical characteristics are also retained throughout the year: less transparent water is retained in the upper layer by the density gradient, while the water below is optically uniform, with $c(660)$ values occasionally increasing near the bottom as a result of re-suspension. Similarities in the average vertical distribution of $c(660)$ and fluorescence suggest that in deep-water areas, changes in optical properties are due to biological processes, and the presence of any riverine material is not visible here.

Both temporal and spatial changes in the inherent optical properties of the Pomeranian Bay follow the pattern already observed in other areas of the Baltic Sea (Sagan 1991, Olszewski *et al.* 1992), regardless of the extreme or exceptional nature of hydrological events come across during observations. It should be noted that the extreme hydrological conditions during the experiment did have an impact on the recorded values of the diffuse attenuation coefficient spectra. In some spectral ranges there were significant differences between K_d values in spring 1996 and summer 1997 (in the blue light band, K_d differed threefold). The high absorption by yellow substance in the freshwater plumes causes the slope of K_d in the blue and green light to steepen and the maximum transmittance waveband to shift into the yellow light band. This effect could have a possible influence on photosynthesis, because the transmittance of light in the chlorophyll *a* absorption maximum is reduced, as is the depth of the euphotic zone.

5. Conclusions

Owing to the unusual hydrographic conditions in the Pomeranian Bay in 1996 and 1997 it is difficult to summarise these results. The range of variability of some of the optical parameters could be regarded as potential maxima. Statistical analysis of the data enables inferences to be made on the impact of the Odra river waters on the optical conditions for photosynthesis.

- From the spatial standpoint, all optical quantities increase near the river mouth. The elevated turbidity of the water near the shore caused by the river's input of suspended and dissolved material reduces the amount of the light that is potentially available for photosynthesis. The spatial range of this process is limited to the shallow part of the Pomeranian Bay. The optical properties of the open part of this region are similar to those of open Baltic waters.

- The seasonal changes in the light attenuation coefficient and fluorescence depend on the biological activity of the region. Variability was greater in the shallow part of the bay.

- Yellow substance absorption and the diffuse attenuation coefficient are negatively correlated with salinity and could be regarded as an indicator of freshwater plumes. The presence of yellow substance in water reduces the transmittance of blue light and causes substantial changes in the spectral composition of the light transmitted to deeper water. The maximum transmittance waveband shifts from the green to the yellow light band when absorption by yellow substance is high.

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