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ORIGINAL RESEARCH ARTICLE

Light absorption by phytoplankton in the southern Baltic and Pomeranian lakes: mathematical expressions for remote sensing applications

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Summary The absorption properties of phytoplankton in surface waters of the Baltic Sea and coastal lakes are examined in the context of their relationships with the concentration of the main photosynthetic pigment, chlorophyll *a*. The analysis covers 425 sets of spectra of light absorption coefficients $a_{ph}(\lambda)$ and chlorophyll *a* concentrations *Chla* measured in 2006—2009 in various waters of the Baltic Sea (open and coastal waters, the Gulf of Gdańsk and the Pomeranian Bay, river mouths and the Szczecin Lagoon), as well as in three lakes in Pomerania, Poland (Obłęskie, Łebsko and Chotkowskie). In these waters the specific (i.e. normalized with respect to *Chla*) light absorption coefficient of phytoplankton $a_{ph}^*(\lambda)$ varies over wide ranges, which differ according to wavelength. For example, $a_{ph}^*(440)$ takes values from 0.014 to 0.124 mg^{-1} m^2, but $a_{ph}^*(675)$ from 0.008 to 0.067 mg^{-1} m^2, whereby *Chla* ranges from 0.8 to 120 mg m^{-3}. From this analysis a mathematical description has been produced of the specific light absorption coefficient of phytoplankton $a_{ph}^*(\lambda)$, based on which the dynamics of its variability in these waters and the absorption spectra in the 400—700 nm interval can be reconstructed with a low level of uncertainty (arithmetic statistical error: 4.09—10.21%, systematic error: 29.63—51.37%).

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The relationships derived here are applicable in local remote sensing algorithms used for monitoring the Baltic Sea and coastal lakes and can substantially improve the accuracy of the remotely determined optical and biogeochemical characteristics of these waters.

1. Introduction

With the rapid development of satellite techniques, remote sensing methods have become integral to studies of the aquatic environment. These methods are based, among other things, on the analysis of radiation signals coming from a water surface. On entering the water, solar radiation interacts with its constituents, becoming absorbed and scattered. These processes shape the remote reflectance spectrum, which therefore contains information on numerous characteristics of the marine environment. Studied by a great many teams of researchers, the relationships between the inherent and apparent optical properties of natural waters and the concentration of the constituents they contain provide the theoretical foundation for remote methods of investigating the environment (Antoine and Morel, 1996; Antoine et al., 1996; Woźniak et al., 2004). The accuracy of the optical models derived from this research governs that of satellite algorithms, enabling a range of important characteristics of the marine environment to be determined. The errors of such algorithms are especially large in the case of coastal sea waters, such as those along the Baltic coast, and inland waters like lakes, because of the strong influence of external factors on their properties (see, for example, Ligi et al., 2017). Progress in the remote sensing of such water bodies thus depends on the development of optical models describing local associations between the constituents of these waters and their optical properties.

One very important process shaping the water-leaving radiation signal is the absorption of light by phytoplankton $a_{ph}(\lambda)$ — more precisely, by the photosynthetic pigments contained in phytoplankton cells, namely, chlorophylls, carotenoids and phycobilins, the composition of which depends on the growing conditions and the species composition of the phytoplankton (Jeffrey and Vesk, 1997; Woźniak and Dera, 2007). The absorption properties of these pigments, in particular the characteristic spectral regions of each one within which light absorption is maximally effective, are linked with the part they play in photosynthesis. Chlorophylls absorb light in the blue (440—475 nm) and red (630—675 nm) regions of the spectrum, while carotenoids and phycobilins do so in the 400—500 nm and 540—650 nm ranges, respectively (Bidigare et al., 1990; Bricaud et al., 2004; Jeffrey and Vesk, 1997). Being a superimposition of the absorption properties of these pigments, the visible light absorption spectra of phytoplankton $a_{ph}(\lambda)$ are characterized by two main bands: a broader one in the blue part of the spectrum with an absorption maximum between 435 and 445 nm, and another, narrower one in the red part of the spectrum with a maximum at ca 675 nm.

In sea waters, the absolute values of absorption coefficients $a_{ph}(\lambda)$ are associated above all with the phytoplankton biomass, the measure of which is assumed to be the concentration of chlorophyll *a*, *Chla* [mg m^{-3}], and can vary over more than three orders of magnitude. Consequently, over the entire visible light spectrum, $a_{ph}(\lambda)$ takes the lowest values in very clear superoligotrophic waters (open ocean) and the highest ones in supereutrophic waters, i.e. coastal waters and enclosed water bodies (Babin et al., 2003; Bricaud et al., 1995, 1998; Woźniak and Dera, 2007). Values of $a_{ph}(\lambda)$ in lacustrine waters likewise vary over more than three orders of magnitude and their optical properties are very similar to those of sea waters, especially those in coastal and estuarine waters (Ficek, 2013; Le et al., 2009).

The development of mathematical models enabling the absorption properties of phytoplankton in natural waters to be determined from the concentrations of certain constituents of such waters, usually chlorophyll *a*, has been going on for many years, both for clear oceanic waters with relatively low chlorophyll *a* concentrations (Bricaud et al., 1995, 1998) and for waters with a much higher phytoplankton content (Ficek et al., 2012a,b; Paavel et al., 2016; Ylöstalo et al., 2014), including those in which external factors exert a considerable influence on their optical properties. Applying these dependences instead of universal remote sensing algorithms developed for monitoring the optical properties of ocean waters is the means by which the accuracy of satellite-based research methods can be improved (see e.g. Darecki and Stramski, 2004; Darecki et al., 2003, 2008; Ficek et al., 2012b; Ligi et al., 2017).

Algorithms derived by different research teams to account for the specific conditions of the Baltic, i.e. the different hydrological, biological and other conditions giving rise to the optical differentiation of the various subareas of this sea, have been analyzed for their accuracy. The results of these analyses have merely served to underscored the validity of their application (Ligi et al., 2017).

On the other hand, the mathematical descriptions of the absorption properties of suspended particulate matter in the Baltic, derived to date by various authors, are applicable to only small areas of this sea (Babin et al., 2003; Riha and Krawczyk, 2013; Seppälä, 2003; Vaičiūtė, 2012; Woźniak et al., 2011), or are restricted to certain regions of the absorption spectrum (Meler et al., 2016a, 2017).

For this reason, the aim of the present paper is to analyze the possibilities of deriving such a local mathematical description of the association between the absorption properties of phytoplankton in southern Baltic coastal waters and three lakes in the Pomeranian Lake District (Poland) and the concentration of chlorophyll *a*.

The areas explored in this paper are examples of optically complex waters which are strongly influenced by external factors. Ocean waters are optically dominated by phytoplankton in contrast to freshwaters, such as lakes, which

contain large amounts of organic and inorganic suspended matter and dissolved humus substances (Strömbeck, 2001). The Baltic Sea is characterized by low salinity (especially coastal and bays waters) and large amounts of chromophoric dissolved organic matter (CDOM) and suspended matter, including phytoplankton. Whereas the proportion of phytoplankton in light absorption by all suspended particles is comparable or slightly higher than the proportion of non-algal particles – Meler et al. (2016a). Similar relationships are observed in Pomeranian lakes (Ficek, 2013). Fresh and inner sea waters (like Baltic) contain large amounts of dissolved substances transported from land through rivers and groundwater. Hence, the contribution of dissolved substances in total light absorption, especially in the short-range visible light, is considerably higher than in most ocean or sea waters, where CDOM is primarily a derivative product of phytoplankton. Therefore the optical properties of the waters analyzed in this work are governed largely by the presence of allo- and autogenic CDOM. The characteristic influence of CDOM on the absorption properties of Baltic Sea and Pomeranian lake waters has been described in detail in numerous papers, e.g. Kowalczuk (1999), Kowalczuk et al. (1999, 2005), Ficek et al. (2012b) and Meler et al. (2016b).

Because of the previously mentioned similarities, mutual spatial relationships and the fact that analyzed regions are affected by similar local factors, it is advisable to undertake an attempt to combined analyze the optical properties of Baltic waters (especially in coastal areas) and Pomeranian lakes. Such parameterization of phytoplankton absorption properties combined with the parameterization of the CDOM absorption properties shown in Meler et al. (2016b), will allow the development of unified parameterization for marine and fresh waters with high CDOM content. Such parameterization will facilitate the development of one model for remote sensing studying these environments.

This relationship is essential, among other things, to the development of remote methods (including satellite-based ones) for studying the waters of the Baltic Sea and coastal lakes, for example, for testing OLCI (Ocean and Land Colour Instrument) products.

2. Material and methods

2.1. Sampling area

Achieving the objectives of this research required the analysis of an extensive set of empirical data, collected in the southern Baltic and three lakes in the Pomeranian Lake District in 2006–2009 (see Fig. 1). The measurements were made during 15 cruises of r/v *Oceania* on the Baltic at the measurement stations shown in Fig. 1 (383 sets of empirical data from the water surface – see Table 1), but at locations inaccessible to the ship (e.g. river mouths, the stations in the Szczecin lagoon), water was obtained from a rubber dinghy. Research cruises were organized to capture the dynamics of natural seasonal variability occurring in temperate waters: (i) at the end of the winter before the onset of the spring phytoplankton bloom, when wind-driven mixing, the vertical convective thermohaline circulation, reduced biological activity and reduced riverine outflow all result in clearer surface waters; (ii) in spring when the spring phytoplankton bloom coincides with maximum freshwater runoff from the Baltic Sea catchment area; (iii) and at the end of summer at the peak of secondary phytoplankton blooms and the period of maximum thermal stratification of waters (see Meler et al., 2016b). Samples were collected over a wide area of the southern Baltic Sea, including the Gulf of Gdańsk, the Pomeranian Bay, the Szczecin Lagoon, Polish coastal waters and the open sea (the Baltic Proper). Bay waters are directly influenced by two major Polish river systems, the Vistula and the Odra. Additionally, samples (66 datasets) were gathered twice a month at the sampling station on the Sopot pier (Gulf of Gdańsk). The empirical data obtained are not, however, appropriate for analysing the absorption properties of waters during cyanobacteria blooms: hence, no measurements were performed during the period typical of such blooms (June–July). Estimates made from analyses of absorption spectra indicate that cyanobacteria can be assumed present in 2–3%

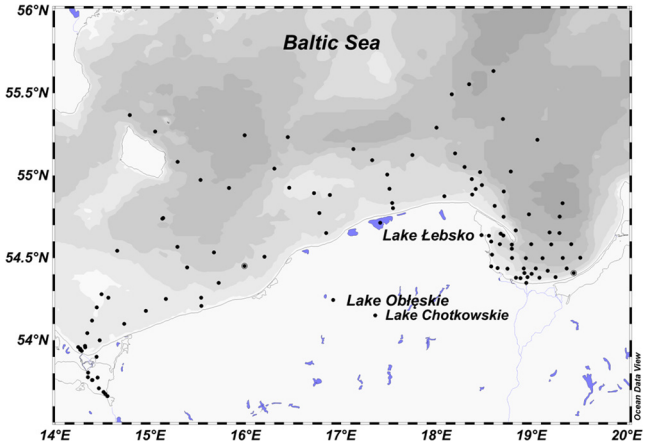

Figure 1 Positions of the stations where data for analysis were gathered.

Table 1 Bio-optical parameters obtained in the study areas.

Parameter	Baltic Sea (n = 383)	Lakes (n = 42)	Total (n = 425)
Chla [mg m^{-3}]	8.39 ± 12.60 (0.84–120.6)	43 ± 35.47 (1.48–118.97)	11.89 ± 19.42 (0.84–120.6)
SPM [g m^{-3}]	2.73 ± 3.12 (0.497–20.04)	16.68 ± 20.52 (1.23–70.67)	5.04 ± 10.17 (0.497–70.67)
$a_{CDOM}(400)$ [m^{-1}]	0.997 ± 0.73 (0.15–4.79)	4.47 ± 2.07 (1.28–8.85)	1.35 ± 1.41 (0.15–8.85)
Validation	(n = 126)	(n = 11)	(n = 137)
Chla [mg m^{-3}]	5.76 ± 9.43 (0.67–95.67)	46.19 ± 36.52 (6.60–103)	9.01 ± 17.4 (0.67–103)

of the water samples, but this has not been confirmed by studies using appropriate measurement techniques.

Measurements on Lakes Łebsko, Chotkowskie and Obłęskie – enclosed water bodies with just small streams/rivers flowing into them – were performed from April 2006 to November 2009, when they were not covered by ice. A total of 42 datasets were acquired from the lakes. The measurements were made once a month; this did not guarantee the recording of shorter-term phenomena like cyanobacteria blooms, which would significantly modify the spectrum of phytoplankton absorption.

Lake Łebsko is a coastal lake, with a river flowing through it, and has a direct connection with the Baltic Sea. Sometimes, as a result of backflows, water from the sea mixes with that in the lake, which causes the latter's water level to rise by about 0.5 m (Chlost and Cieśliński, 2005) and affects the composition and properties of the lacustrine water. Lake Łebsko is the third largest lake in Poland (70.2 km^2) and the mean depth is 1.6 m. The waters of Lake Łebsko are hypertrophic (mean annual *Chla* > 82 mg m^{-3}, variability 40–130.4 mg m^{-3} – see Ficek (2013)). In contrast, the eutrophic Lakes Chotkowskie (0.53 km^2, mean depth 5.4 m) and Obłęskie (0.63 km^2, mean depth 6.2 m) lie some 80 km from the Baltic coast; mean annual *Chla* in these lakes is 28.1 mg m^{-3} (1.5–91.1 mg m^{-3}) and 14.8 mg m^{-3} (2–34.5 mg m^{-3}) respectively (Ficek, 2013). The properties of their waters are modified by the riverine waters flowing into/through them.

In addition, independent datasets collected during 5 cruises on the Baltic in 2011 (126 sets) and from lakes (11 sets), not used for the calculations, were used for validating the parameterizations derived in this work.

2.2. Sample processing

The data to be analyzed included the following parameters, determined in the laboratory in surface water samples:

- light absorption coefficient $a_{ph}(\lambda)$ [m^{-1}], determined in the 400–700 nm spectral range from the difference between the optical density of the suspended particulate matter accumulated on the filter and that of the same material deprived of absorbing pigments. This parameter was measured in a UNICAM UV4-100 double beam spectrophotometer equipped with a LABSPHERE RSA-UC-40 integrating sphere of external diameter 66 mm, in accordance with the methodology given by Tassan and Ferrari (1995, 2002), Mitchell (1990) and Stramska et al. (2006) (a detailed description of sample treatment and the relevant methodology is given in Meler et al., 2017 and Woźniak et al., 2011);
- chlorophyll *a* concentration *Chla* [mg m^{-3}], determined spectrophotometrically after 24 h extraction in 96% ethanol (Marker et al., 1980; Wintermans and DeMots, 1965). The optical density (*OD* = absorbance) of the pigment extract in ethanol was measured at 665 nm. After correction for the background signal in the near-infrared (750 nm):

$$\Delta OD = OD(665\,\text{nm}) - OD(750\,\text{nm}), \quad (1)$$

the absorbance was converted to *Chla* using Eq. (2), using the volumes of filtered water (V_w) [dm^3] and the ethanol extract (V_{EtOH}) [cm^3], a 2 cm cuvette path length (l) and the specific absorption coefficient of chlorophyll *a* in 96% ethanol [dm^3 (g cm)$^{-1}$] (Sartory and Grobbelaar, 1984; Stramska et al., 2003) (a detailed description of the sample treatment and the relevant methodology is given in Meler et al., 2016b):

$$Chla = \frac{10^3 \cdot \Delta OD \cdot V_{EtOH}}{(83 \cdot V_w \cdot l)^{-1}}. \quad (2)$$

The specific absorption coefficients of chlorophyll *a* by phytoplankton pigments $a_{ph}^*(\lambda)$ [mg^{-1} m^2] were calculated using the formula:

$$a_{ph}^*(\lambda) = \frac{a_{ph}(\lambda)}{Chla}. \quad (3)$$

The data analyzed in this work were gathered in very different waters, in which bio-optical parameters like *Chla* and SPM (suspended particulate matter) concentrations or CDOM absorption coefficient (see Meler et al., 2016b) exhibited a wide range of variability (see Table 1). The Baltic Sea dataset (n = 383) contains mostly samples with *Chla* = 1–10 mg m^{-3} range (n = 306), but also samples with higher *Chla* levels, i.e. in the 10–20 mg m^{-3} (n = 43), 20–50 mg m^{-3} (n = 28) and 50–120 mg m^{-3} (n = 6) ranges. The lacustrine water dataset (n = 42) contains n = 10, 4, 11 and 17 samples, respectively, in the above *Chla* ranges.

These waters lie in a climate zone where seasonal variability is large, which implies a series of phytoplankton assemblages in the successive seasons. They are of a semi-enclosed or enclosed nature, and their optical properties are strongly affected by extraneous substances. It should also be stressed that these data are characteristic of eutrophic water bodies, in which the level of biological productivity is relatively high.

3. Results and discussion

3.1. Variability of chlorophyll-specific phytoplankton absorption in the southern Baltic and Pomeranian Lakes

As already mentioned, the main factor affecting the value of $a_{ph}^*(\lambda)$ is the concentration of chlorophyll *a* *Chla*, treated as the index of phytoplankton biomass in a water body. Nonetheless, the shape of the absorption spectrum also depends on the absorption properties of photosynthetic pigments contained in algal cells in a water body and on a number of other factors, including external ones. This becomes obvious once absorption coefficient spectra have been normalized with respect to *Chla*. The spectrum of $a_{ph}^*(\lambda)$ enables one to track the absorption properties of the phytoplankton characteristic of a given water body independently of the chlorophyll concentration. The pigments participating in photosynthesis can be divided into three groups: chlorophylls, carotenoids and phycobilins. Fig. 2 shows a selection of spectra of $a_{ph}(\lambda)$ (Fig. 2a and b) from the datasets examined, together with their corresponding specific coefficients $a_{ph}^*(\lambda)$ (Fig. 2c and d), covering the entire range of values recorded in the Baltic and the three Pomeranian lakes. The spectra show the two main peaks of $a_{ph}(\lambda)$, due to the absorption of light by chlorophyll *a*, the main bands of which lie in the blue and red regions of the spectrum, as well as the influence of the other photosynthetic pigments present in

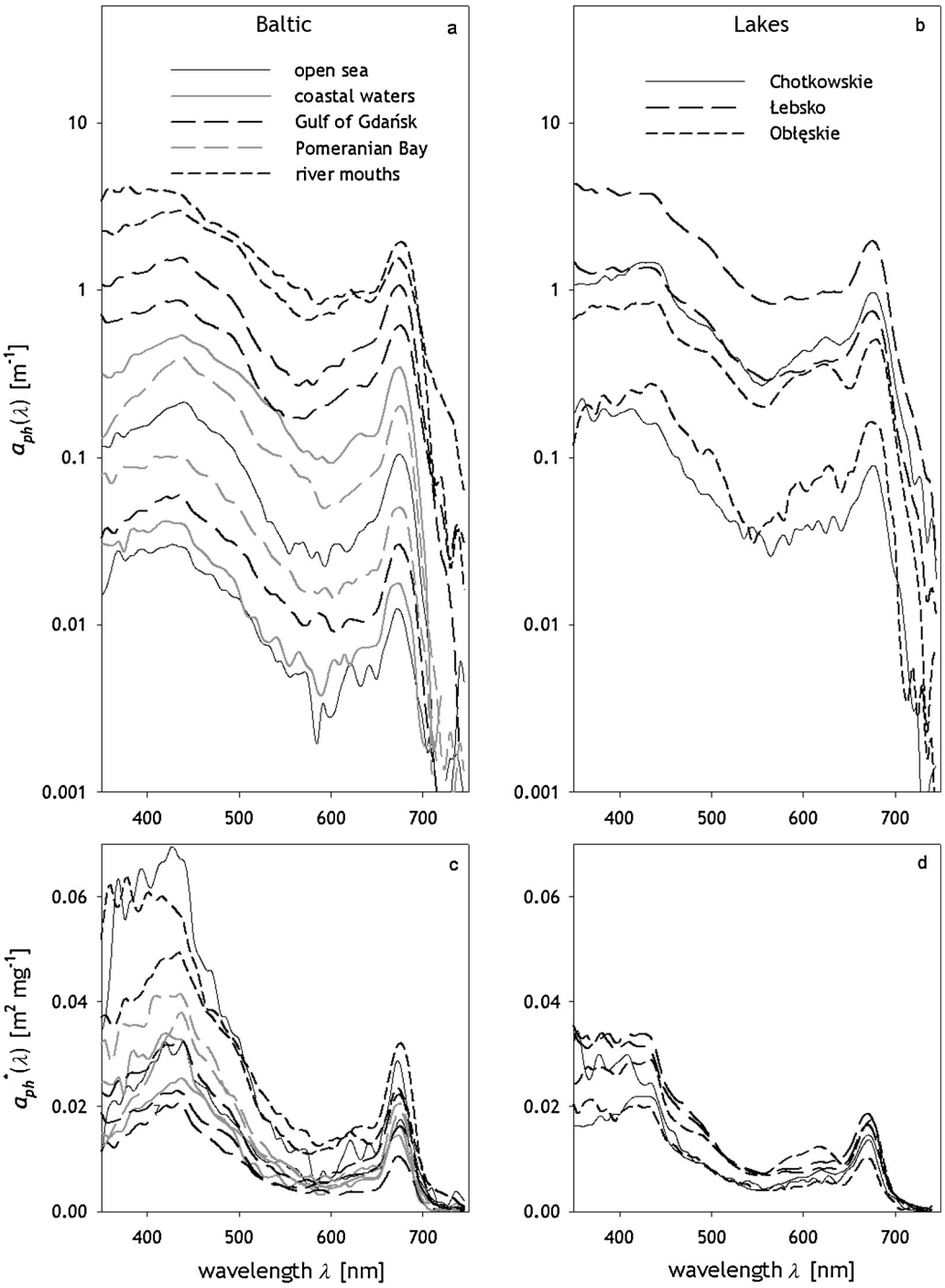

Figure 2 Measured spectra of light absorption coefficients $a_{ph}(\lambda)$: (a) in the Baltic Sea, (b) in three Pomeranian lakes, and specific light absorption coefficients $a_{ph}^{*}(\lambda)$: (c) in the Baltic Sea, (d) in three Pomeranian lakes.

phytoplankton cells. The larger of these peaks lies in the 435—445 nm interval. Its width and height are determined by light absorption by both chlorophyll *a* and the other pigments in phytoplankton. On the other hand, the second absorption band lies in the red part of the spectrum with a maximum at around 675 nm. In this region of the spectrum, light is absorbed almost exclusively by chlorophyll *a*, so this band is usually shorter and narrower than the short-wave one. It can be seen in Fig. 2 that in both the Baltic and the lakes there are smaller and narrower absorption bands that depend on the various optical admixtures in the suspended matter contained in the water. For example, such a local maximum occurs during blooms of cyanobacteria or red algae: these contain phycobilins, which absorb light in the middle region of the spectrum (540—650 nm — Jeffrey and Vesk, 1997). It is worth recalling that this region of the spectrum also shows the absorption maximum of chlorophyll *b* and its derivatives.

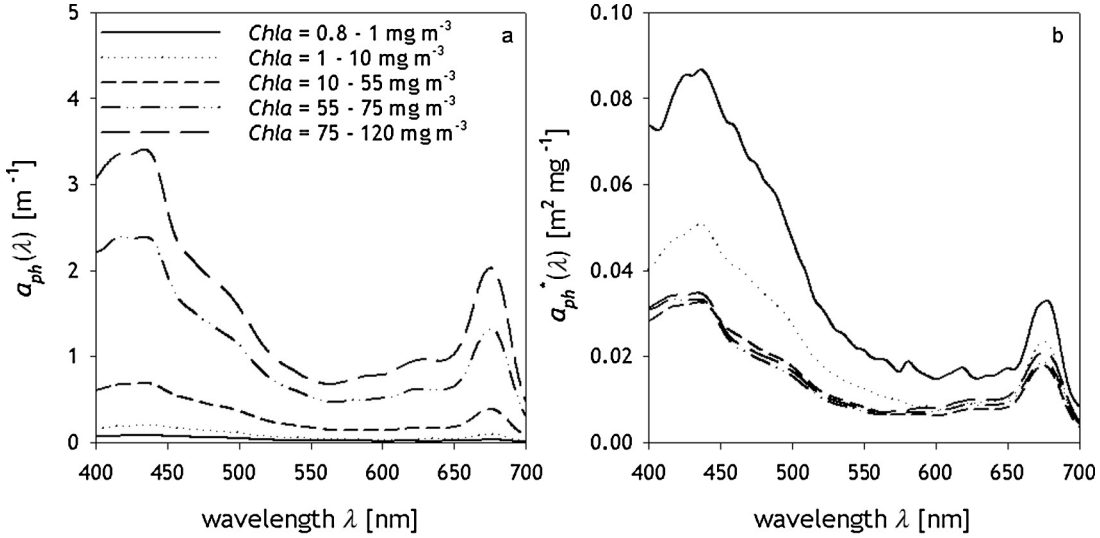

Figure 3 Averaged spectra in selected chlorophyll *a* concentration intervals: measured phytoplankton light absorption coefficients (a) and the corresponding specific phytoplankton absorption coefficients (b). *Chla* intervals: 0.8—1 mg m^{-3} (mesotrophic waters), 1—10 mg m^{-3} (weakly eutrophic waters), 10—55 mg m^{-3} (medium eutrophic waters), 55—75 mg m^{-3} (eutrophic waters), 75—120 mg m^{-3} (hypereutrophic waters).

Fig. 3a shows the mean values of phytoplankton light absorption spectra in five concentration ranges, determined from measurements in the Baltic Sea and Pomeranian lakes, while Fig. 3b shows the corresponding mean specific absorption spectra for the same ranges of *Chla*. The features associated with the composition of pigments and their mutual proportions, characteristic of the water bodies investigated here, are very distinct in both plots. The trophic classification in Fig. 3 is somewhat arbitrary, as the classifications are different for seas/oceans and lakes. The trophicities of seas and oceans were taken from Woźniak et al. (1992a,b) and Woźniak and Dera (2007). According to this classification, these waters can be categorized as oligotrophic (*Chla* < 0.2 mg m^{-3}), mesotrophic (*Chla* = 0.2—1 mg m^{-3}), eutrophic (*Chla* = 1—100 mg m^{-3}) and hypereutrophic (*Chla* > 100 mg m^{-3}).

According to Choiński (2007), lacustrine waters can be classified as ultraoligotrophic (*Chla* < 2.5 mg m^{-3}), oligotrophic (*Chla* = 2.5—8 mg m^{-3}), mesotrophic (*Chla* = 8—25 mg m^{-3}), eutrophic (*Chla* = 25—55 mg m^{-3}), hypereutrophic (*Chla* > 55 mg m^{-3}) and dystrophic (in which production is based mostly on allochthonous matter, the amount of carbon organic is large and concentrations of humic substances are high — in contrast to conventional oligotrophic lakes which also have a low level of primary production). The trophic classification in lakes is determined not only by the *Chla* concentration, but also additionally on the basis of water transparency (determined by Secchi disk) and the concentrations of biogenic factors, i.e. nitrogen and phosphorus (Carlson, 1977; Kratzer and Brezonik, 1981; Vollenweider and Kerekes, 1982). Fig. 3 shows the trophic division taking into account both marine and lacustrine waters: mesotrophic waters (*Chla* = 0.8—1 mg m^{-3}), weakly eutrophic waters (*Chla* = 1—10 mg m^{-3}), medium eutrophic waters (*Chla* = 10—55 mg m^{-3}), eutrophic waters (*Chla* = 55—75 mg m^{-3}) and hypereutrophic waters (*Chla* = 75—120 mg m^{-3}).

3.2. Parameterizations of chlorophyll-specific phytoplankton absorption

The standard mathematical formula derived by Bricaud et al. (1995) is used to describe and determine the absorption properties of phytoplankton. It enables one to determine the spectrum of the specific phytoplankton absorption (i.e. normalized with respect to the *Chla*) in a water body on the basis of known *Chla*:

$$a_{ph}^*(\lambda) = A(\lambda) Chla^{-B(\lambda)}, \quad (4)$$

where $A(\lambda)$ and $B(\lambda)$ are wavelength-dependent parameters statistically determined for the 400—700 nm range.

This mathematical form of the relationship allows one to take into account the effect of the other photosynthetic pigments presence on the absorption properties of phytoplankton, i.e. the packaging effect, which vary with wavelength and are strongly dependent on external factors. This form has already been used to describe the absorption properties of phytoplankton in various water bodies (e.g. Dmitriev et al., 2009; Ficek et al., 2012a; Paavel et al., 2016; Reinart et al., 2004; Stæhr and Markager, 2004; Ylöstalo et al., 2014; Yoshimura et al., 2012).

Fig. 4 shows the dependence of the specific phytoplankton light absorption coefficients $a_{ph}^*(\lambda)$ on *Chla* for the four most characteristic wavelengths; Table 2 lists their ranges and mean values in the dataset. As already mentioned, light absorption by chlorophyll *a* peaks at wavelengths 440 nm and 675 nm. In contrast, the absorption spectrum is the least variable at 500 nm, and at 600 nm the light absorption by phytoplankton drops to a local minimum.

Gathered in both saline and fresh waters, this dataset is evidently coherent and indicates the uniform nature of this dependence across the whole range of variability. Nonetheless, low values of $a_{ph}^*(\lambda)$ at high *Chla* are recorded mainly in lakes and river mouths, where the differences in pigment

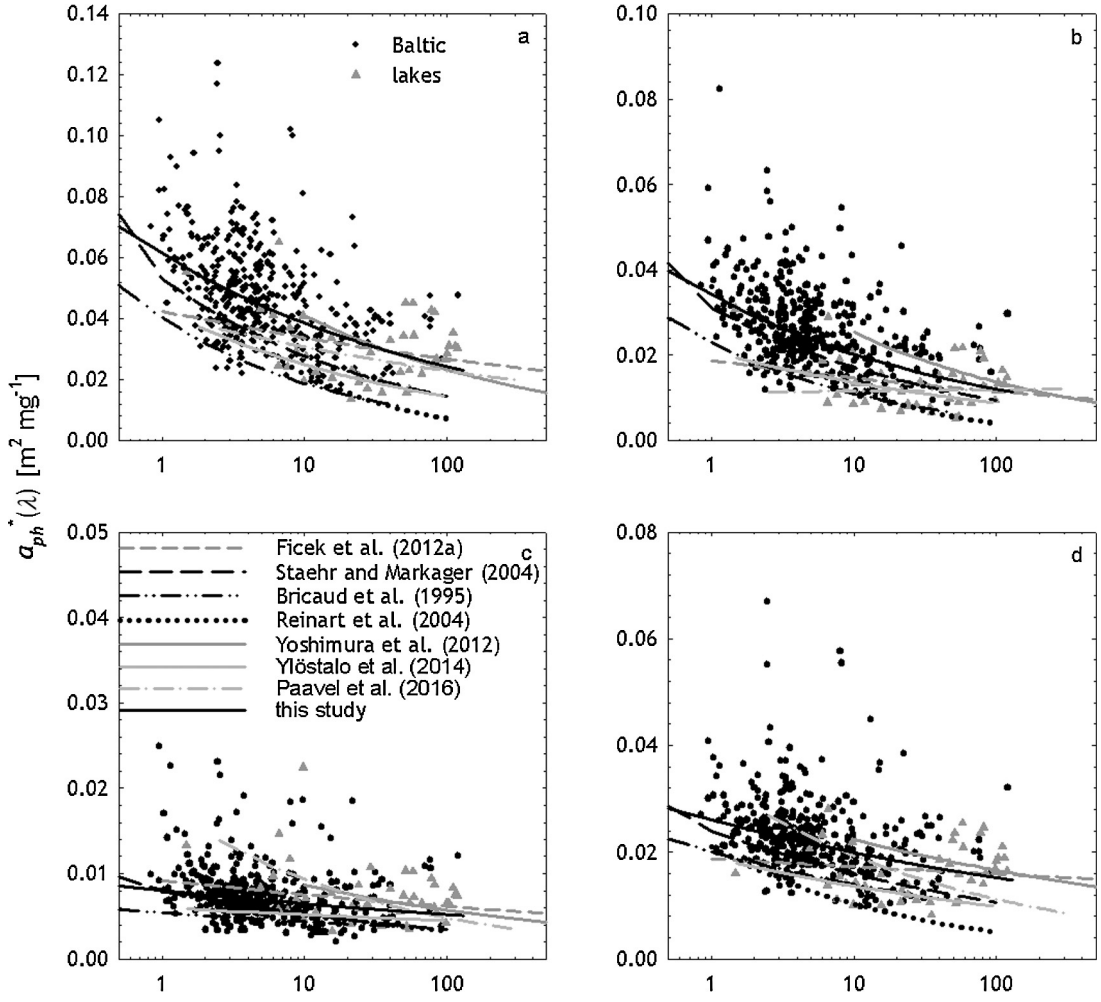

Figure 4 Dependence of coefficients $a_{ph}^*(\lambda)$ on chlorophyll *a* concentrations (*Chla*) for wavelengths: (a) 440 nm, (b) 500 nm, (c) 600 nm, (d) 675 nm. The circles and triangles respectively represent data relating to the Baltic Sea and the lakes. The lines represent the dependences derived by various authors for the water bodies they studied.

Table 2 Range, average values and standard deviations of the specific absorption coefficients $a_{ph}^*(\lambda)$ at selected wavelengths.

Region	Range/average values $a_{ph}^*(\lambda)$ [m^2 mg^{-1}]			
	λ = 440 nm	λ = 500 nm	λ = 600 nm	λ = 675 nm
Baltic Sea	0.016–0.124	0.009–0.082	0.002–0.025	0.009–0.067
	0.048 ± 0.017	0.026 ± 0.010	0.008 ± 0.003	0.023 ± 0.007
Lakes	0.014–0.065	0.005–0.031	0.003–0.022	0.008–0.028
	0.030 ± 0.011	0.013 ± 0.006	0.008 ± 0.004	0.016 ± 0.005
Total	0.014–0.124	0.005–0.082	0.002–0.025	0.008–0.067
	0.046 ± 0.017	0.025 ± 0.010	0.008 ± 0.003	0.022 ± 0.007

composition are usually large (Ficek, 2013; Ylöstalo et al., 2014).

The various lines in Fig. 4 show the dependences calculated using Eq. (4) based on statistical analyses of absorption spectra from different water bodies. These dependences refer to surface waters; only in the case of Bricaud et al. (1995) does the relevant data set contain samples from different depths. These waters exhibited several ranges of variability of *Chla* and $a_{ph}^*(\lambda)$. The parameterization of Bricaud et al. applied to clear oceanic waters, in which *Chla* ranged from 0.01 to 25 mg m^{-3}, and $a_{ph}^*(\lambda)$ at the blue absorption peak varied from 0.01 to 0.18 m^2 mg^{-1}. Stæhr and Markager (2004), on the other hand, derived a mathematical description of the absorption properties of phytoplankton based on data containing a wider range of *Chla* (0.03–88.1 mg m^{-3}), measured in coastal oceanic waters,

where $a_{ph}^*(440)$ ranged from 0.015 to 0.19 $m^2\ mg^{-1}$. Ficek et al. (2012a) derived a parameterization for Pomeranian lakes covering a very broad range of *Chla* (1.2–336 mg m^{-3}) and $a_{ph}^*(440)$ (0.005–0.2 $m^2\ mg^{-1}$). Parameterizations have also been derived for other lakes: for example, that by Reinart et al. (2004) illustrates the results of a study of Lake Peipsi in Estonia, in which *Chla* was 1.8–95 mg m^{-3}, and the one by Yoshimura et al. (2012), who performed a similar analysis for Lake Kasumigaura in Japan, where *Chla* ranged from 36.6 to 214.4 mg m^{-3} and $a_{ph}^*(440)$ from 0.012 to 0.051 $m^2\ mg^{-1}$. The another parameterizations in Fig. 4 are for Finnish lakes – Ylöstalo et al. (2014), where *Chla* ranged from 1.80 to 94.7 mg m^{-3} and $a_{ph}^*(440)$ from 0.01 to 0.18 $m^2\ mg^{-1}$, and Estonian lakes – Paavel et al. (2016), where *Chla* ranged from 2.7 to 315.4 mg m^{-3} and $a_{ph}^*(440)$ from 0.012 to 0.053 $m^2\ mg^{-1}$. All the relationships presented in Fig. 4 utilize the close dependence of the absorption properties of phytoplankton on chlorophyll *a*. Here, it should be noted that for every wavelength $a_{ph}^*(\lambda)$ falls in value with increasing chlorophyll *a* concentration. Among other things, this is due to the packaging effect, which increases with rising chlorophyll *a* concentrations and the decreasing relative proportion of the other pigments (Bricaud et al., 1995; Morel and Bricaud, 1981; Woźniak et al., 1999, 2000). It is noticeable, however, that the rate of this decrease differs, not only in different regions of the spectrum but also in each of the water bodies analyzed in the mentioned above papers. This is due to the significant influence of a number of environmental factors, mentioned earlier, on the optical properties of the various waters. Consequently, none of the relationships shown in Fig. 4, calculated for other waters, reflects the nature of the connection between the absorption properties of phytoplankton and the chlorophyll *a* concentration in the waters in our study area. The parameterizations by Bricaud et al. (1995) and Reinart et al. (2004) distinctly underestimate the values of $a_{ph}^*(\lambda)$ for the waters studied here, their assumption being that these values fall too quickly with increasing *Chla* over the whole range of variability. The dependences of $a_{ph}^*(\lambda)$ on *Chla* derived by Stæhr and Markager (2004) also assume that $a_{ph}^*(\lambda)$ should drop faster with increasing *Chla*. In contrast, the parameterization by Ficek et al. (2012a) clearly underestimates $a_{ph}^*(\lambda)$ for $Chla < 10$ mg m^{-3}. The parameterization by Yoshimura et al. (2012) for water bodies with high chlorophyll concentrations reflects the character of the dependence of $a_{ph}^*(\lambda)$ on *Chla* only when the latter factor >20 mg m^{-3}. Neither of these parameterizations derived for lakes are sufficiently universal to describe with satisfactory accuracy the properties of phytoplankton in the southern Baltic. This is due, inter alia, to the lower values of *Chla* usually recorded in this inland sea. The parameterization by Ylöstalo et al. (2014) underestimates $a_{ph}^*(\lambda)$ over practically the entire range of *Chla*, just like the parameterization of Bricaud et al. (1995) mentioned above. Again, the parameterization by Paavel et al. (2016), like the one by Ficek et al. (2012a), evidently underestimates $a_{ph}^*(\lambda)$ for $Chla < 10$ mg m^{-3}, although for $Chla > 10$ mg m^{-3} this underestimation is not so great. For wavelength 600 nm, it is clear that the parameterization by Paavel et al. (2016) clearly overestimates $a_{ph}^*(\lambda)$. This may mean a lack of or a very small number of samples indicating the presence of cyanobacteria (which absorb light mainly in the 540–650 nm range – Jeffrey and Vesk, 1997) in the dataset analyzed in this paper in comparison with the samples analyzed by Paavel et al. (2016).

It should therefore be remembered that determining absorption coefficients of phytoplankton on the basis of chlorophyll *a* concentrations in different water bodies using a single universal model that does not take account of local conditions can lead to serious errors. Accuracy can be improved by applying multicomponental dependences that take the effect of other environmental factors or parameters into consideration or by deriving specific local relationships (Majchrowski, 2001; Woźniak et al., 2003). Such a local dependence, determined for the water bodies we have been studying and based on an extensive dataset, is shown by the continuous black line in Fig. 4. The present paper analyses the data base as a whole, and also separately for southern Baltic waters and the waters of three Pomeranian lakes. The coefficients $A(\lambda)$ and $B(\lambda)$ of this dependence as a function of wavelength are listed in Table 3 for all data (Baltic and lakes) and also in Table A1 (only Baltic) and Table A2 (only lakes) – see Appendix.

Fig. 5 shows coefficients *A* and *B* of the parameterization of chlorophyll-specific phytoplankton absorption for the data: the southern Baltic and Pomeranian Lakes combined, the southern Baltic only and Pomeranian Lakes only. It is clear from the figure that A for all the data and for the Baltic alone takes very similar values (see Table 3 and Table A1) – there are only very fine differences in the 450–560 nm wavelength interval. In contrast, coefficient *A* for the lakes has quite a different shape.

3.3. Comparison of parameterizations for natural waters

The four wavelengths in Fig. 4 are sufficient to demonstrate that Eq. (4), used to describe the dependence of absorption properties on chlorophyll concentration, takes account of the different nature of this relationship in each of these waters. The variability among the spectra of these coefficients stems primarily from the fact that these dependences were derived for waters of different optical properties, which are due to the composition of the waters (concentration ranges of *Chla* and other optically significant substances, the presence or absence of particular assemblages of phytoplankton, different environmental conditions, presence of dissolved substances etc.). Different environmental conditions, above all irradiance, and the different phytoplankton species composition, and hence the different sets of pigments, lead to various values of specific absorption coefficients at the same concentrations of chlorophyll for each wavelength shown in Fig. 4. The decrease in value of these coefficients due to increasing chlorophyll concentrations is also a characteristic of each water body. This is seen in more detail in Fig. 6, which compares the spectra of coefficients $A(\lambda)$ and $B(\lambda)$ in Eq. (4), determined for all the relationships shown in Fig. 4. These were: ocean waters (Bricaud et al., 1995); ocean and coastal waters (Stæhr and Markager, 2004), Pomeranian lakes (Ficek et al., 2012a), Lake Peipsi (Reinart et al., 2004), Lake Kasumigaura (Yoshimura et al., 2012), Finnish lakes (Ylöstalo et al., 2014) and Estonian lakes (Paavel et al., 2016). It is also worth recalling that in some cases the above relationships were derived for a pre-selected set of spectra with specific

Table 3 Values of parameters $A(\lambda)$ [m^2 mg^{-1}] and $B(\lambda)$ [dimensionless] obtained by fitting the variability of $a_{ph}^*(\lambda)$ with respect to *Chla*, in accordance with Eq. (4) for the 400—700 nm range, with a 5 nm step.

λ [nm] 1	*A* 2	*B* 3	λ [nm] 1	*A* 2	*B* 3	λ [nm] 1	*A* 2	*B* 3
400	0.046	0.156	505	0.031	0.222	610	0.008	0.074
405	0.049	0.163	510	0.028	0.219	615	0.009	0.070
410	0.052	0.170	515	0.025	0.218	620	0.009	0.065
415	0.055	0.176	520	0.023	0.219	625	0.009	0.063
420	0.057	0.182	525	0.021	0.219	630	0.010	0.067
425	0.058	0.188	530	0.019	0.217	635	0.010	0.077
430	0.060	0.194	535	0.018	0.216	640	0.010	0.085
435	0.062	0.199	540	0.017	0.216	645	0.010	0.087
440	0.061	0.200	545	0.016	0.219	650	0.011	0.085
445	0.058	0.202	550	0.016	0.220	655	0.012	0.080
450	0.055	0.210	555	0.015	0.222	660	0.015	0.086
455	0.053	0.223	560	0.014	0.218	665	0.020	0.098
460	0.052	0.234	565	0.013	0.213	670	0.024	0.110
465	0.050	0.240	570	0.012	0.200	675	0.026	0.116
470	0.049	0.242	575	0.011	0.179	680	0.025	0.113
475	0.046	0.244	580	0.010	0.147	685	0.019	0.097
480	0.044	0.242	585	0.010	0.129	690	0.012	0.073
485	0.042	0.241	590	0.009	0.112	695	0.007	0.050
490	0.040	0.237	595	0.009	0.103	700	0.004	0.042
495	0.037	0.231	600	0.008	0.093			
500	0.034	0.225	605	0.008	0.082			

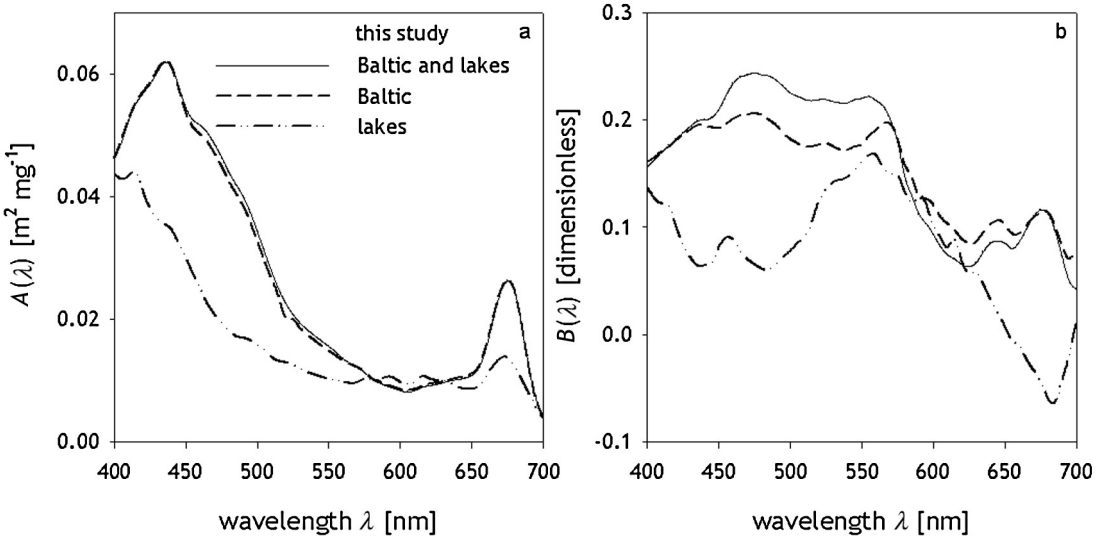

Figure 5 Coefficients *A* and *B* of the parameterizations of phytoplankton absorption for all the data (Baltic and lakes combined) and separately for Baltic and lake waters.

spectral characteristics. Stæhr and Markager (2004), for example, extracted from their data set absorption spectra in which the influence of phaeopigments was apparent in the 420 nm region.

Clearly, then, coefficient $A(\lambda)$ in the model presented here takes higher values than in the models based on ocean waters, but lower ones than those based on lacustrine waters (apart from the results for Pomeranian lakes) across the whole spectral range. Since values of $A(\lambda)$ correspond to values of $a_{ph}^*(\lambda)$ for *Chla* = 1 mg m^{-3}, its spectrum has two main peaks and is similar in shape in the case of all the relationships being analyzed here; however, the spectra of $A(\lambda)$ determined only for a single water body have a much more intricate structure than those based on measurements from many different waters. There are also certain differences in the positions of the two main peaks (ca 420—440 nm in the Soret band and ca 675 nm in the red region) and in the occurrence of local maxima in the short-wave part of the

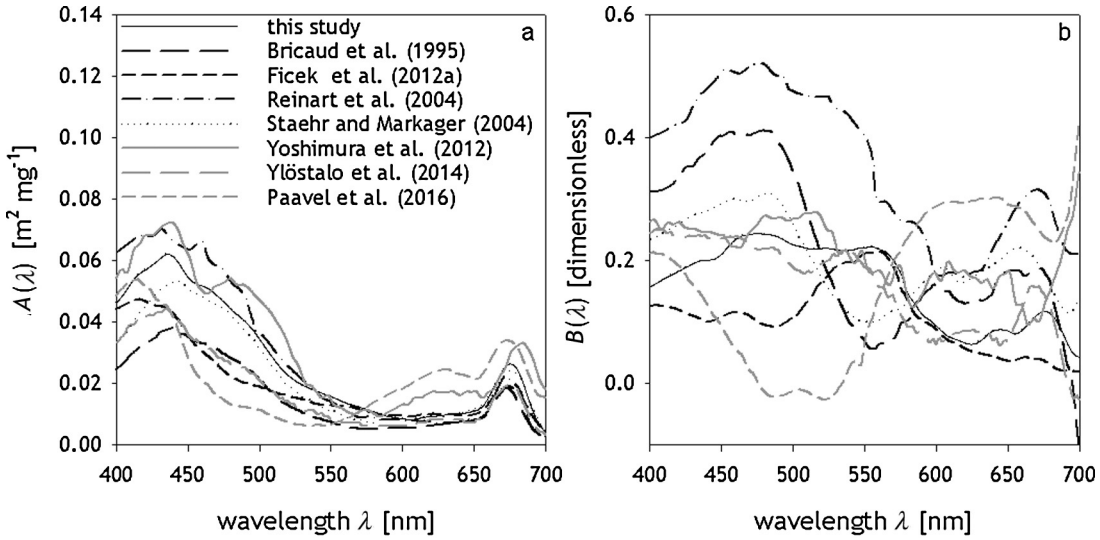

Figure 6 Comparison of the spectral values of parameters $A(\lambda)$ and $B(\lambda)$ in Eq. (4) obtained by various authors.

spectrum, which are due largely to the different concentrations of accessory pigments in the phytoplankton of the waters investigated in this work. There are also local maxima in the 450–500 nm region, but their precise positions vary from one paper to another (e.g. ca 460 nm – Reinart et al. (2004), ca 490 nm – Yoshimura et al. (2012)). The different heights of these peaks are due to the different concentrations of accessory pigments present in the phytoplankton of these waters. In the middle range of the spectrum, i.e. 550–650 nm, values of $A(\lambda)$ are generally low. A certain exception is the hypereutrophic Lake Kasumigaura: in the 580–660 nm region from the relevant spectrum there is a relatively high local maximum, probably due to the high concentrations of phycobilins (phycocyanins) in the phytoplankton of this lake (Naguit and Tisera, 2009; Yoshimura et al., 2012).

The contribution of phycobilins to absorption properties is also evident in the water bodies explored in this paper. Fig. 2 shows a small peak in the 600–650 nm region on both the absorption and specific absorption spectra: this is due to phycobilins. This peak also appears on the averaged spectra shown in Fig. 3 and is reflected in the shape of parameter $A(\lambda)$ in our parameterization. Although this maximum is small in comparison with the parameterization of Yoshimura et al. (2012) or Paavel et al. (2016), it adequately reflects the complex composition of pigments found in the water bodies investigated in this work. The water samples from the Baltic and the lakes were not, however, analyzed for phycobilins.

Coefficient $B(\lambda)$ describes the changes in coefficients $a_{ph}^{*}(\lambda)$ with changes in chlorophyll *a* concentrations. Fig. 6b shows that $a_{ph}^{*}(\lambda)$ is far more variable than parameter $A(\lambda)$ in both spectral shape and values. In the case of the Baltic Sea and the Pomeranian lakes $B(\lambda)$ takes relatively low values in both the blue and the red regions of the spectrum: this is due to the far smaller variability of coefficients $a_{ph}^{*}(\lambda)$ with changes in *Chla* than in ocean waters. Only Ficek et al. (2012a) and Paavel et al. (2016) acquired lower values. For the dependence derived for these waters, there is a local maximum of $B(\lambda)$ in the middle region (500–600 nm), indicative of phycobilins absorbing light in the 540–560 nm region (Ficek, 2013; Sobiechowska-Sasim et al., 2014). A similar maximum occurs in the relationships derived for the Pomeranian lakes and for Finnish lakes (Ylöstalo et al., 2014). In this region of the spectrum for other waters, $B(\lambda)$ frequently takes low values, suggesting the minimal dependence of absorption on chlorophyll (Bricaud et al., 1995). Parameter $B(\lambda)$ derived by Paavel et al. (2016) differs in shape from the others both in the short- and the long-wave regions of the spectrum. There are two local maxima at ca 420 nm and in the 600–660 nm interval, and two other local minima for wavelengths ca 485 nm and ca 520 nm. The peak at ca 420 nm is due to phaeopigments, while that in the 600–660 nm interval, and especially the one between 615 and 645 nm, is due to cyanobacteria (Jeffrey and Vesk, 1997). The minima in the green region of the spectrum are caused by the low values of $a_{ph}^{*}(\lambda)$ and the very low correlation with the chlorophyll concentration.

The specific phytoplankton absorption spectra determined from the dependence derived for four chlorophyll *a* concentrations (1, 10, 50 and 100 mg m^{-3}) are shown in Fig. 7a. For comparison, Fig. 7b shows averaged (for the *Chla* ranges 0.96–1.05 mg m^{-3}, 9.80–10.20 mg m^{-3}, 48–52 mg m^{-3} and 98–102 mg m^{-3}) spectra of $a_{ph}^{*}(\lambda)$ obtained from measurements in the study area. Clearly, the dependence is a good reflection of the characteristic features of measured spectra associated with the composition of pigments typical of the study area. Values of $a_{ph}^{*}(\lambda)$ are underestimated by a few per cent in the case of fairly low chlorophyll concentrations (1 mg m^{-3}), especially in the region around 440 nm. For such low chlorophyll concentrations, closer to the means obtained in the study area, values of $a_{ph}^{*}(\lambda)$ can be obtained by applying the dependence of Bricaud et al. (1995). Fig. 8a shows, however, that the specific absorption spectrum of phytoplankton calculated from that dependence differs widely in shape from the spectra determined empirically in the target waters.

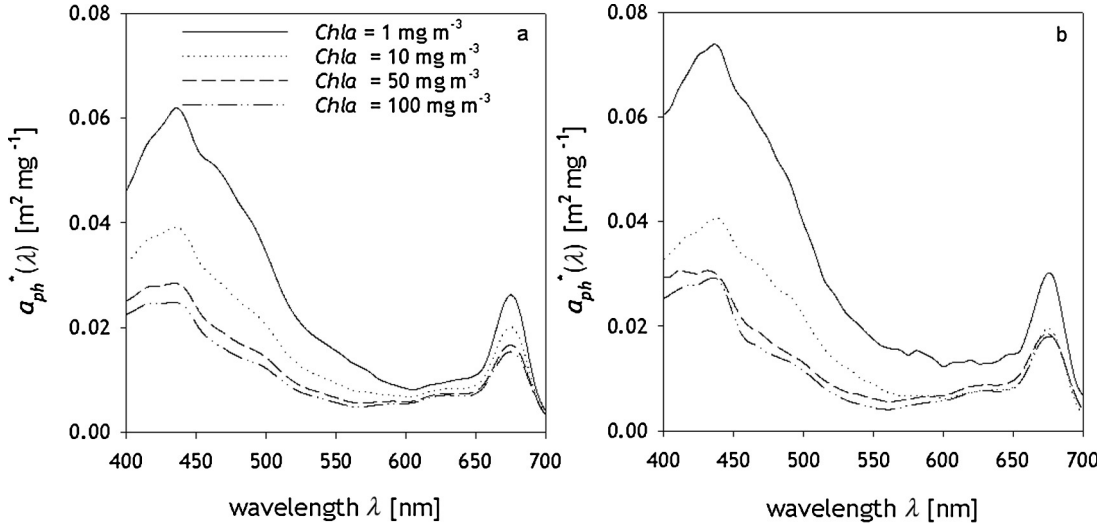

Figure 7 Spectra of specific coefficients of light absorption by phytoplankton $a_{ph}^*(\lambda)$ in the water bodies under study, determined using Eq. (4) (a), and averaged for selected concentrations of chlorophyll *a* (b).

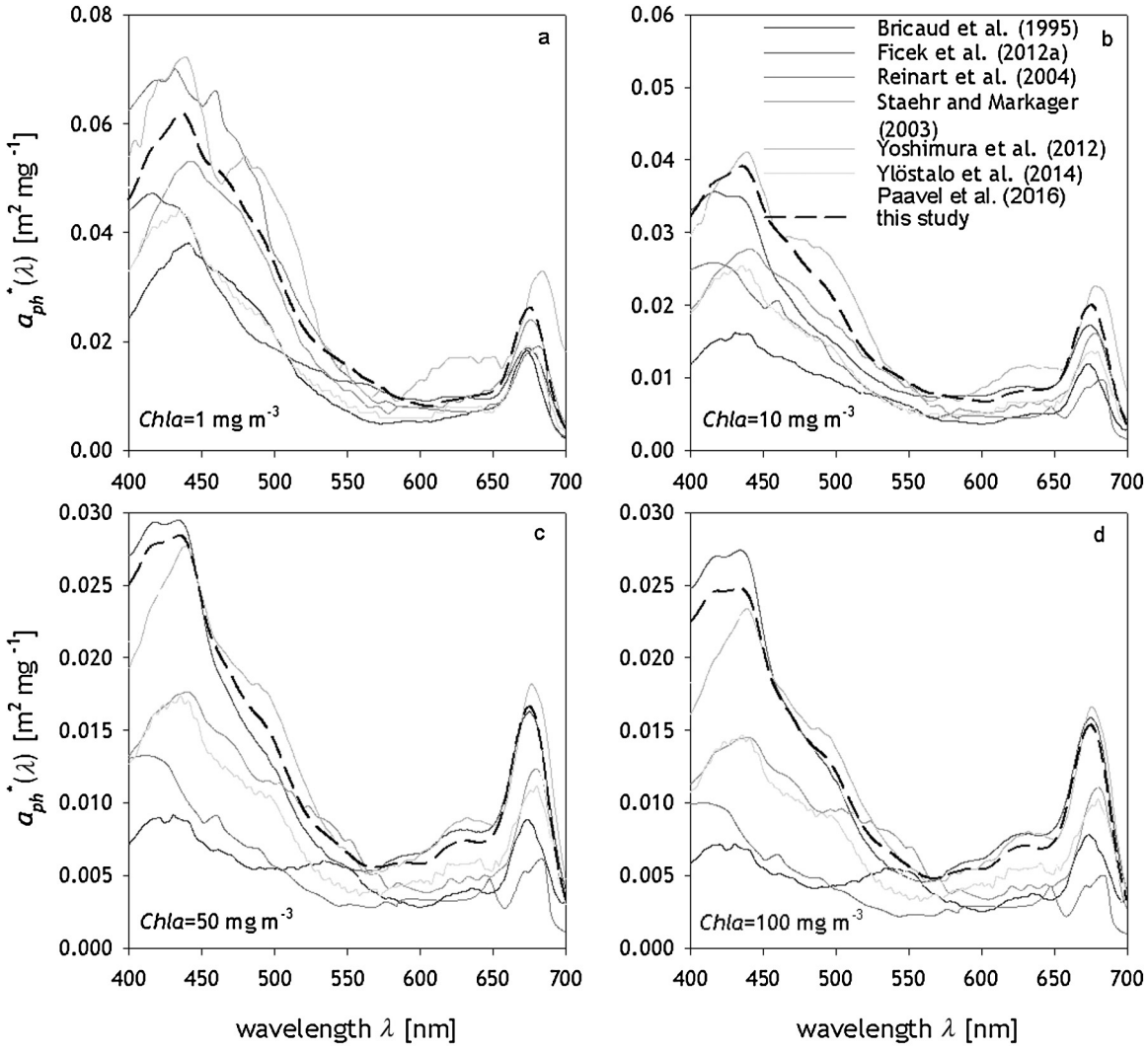

Figure 8 Spectra of specific coefficients of light absorption by phytoplankton $a_{ph}^*(\lambda)$ determined for different concentrations of chlorophyll *a* (*Chla*) using formulas derived by different authors for different water bodies.

Fig. 8a–d show spectra of $a_{ph}^{*}(\lambda)$ obtained using various relationships for four chlorophyll concentrations, covering the whole range of variability in the data. For all the relationships, $a_{ph}^{*}(\lambda)$ falls in value with increasing *Chla* over the entire spectral region.

The differences in the spectral course of $a_{ph}^{*}(\lambda)$ are best illustrated by the position and shape of the peak in the short-wave region. This, as mentioned earlier, is due mainly to changes in the accessory pigment composition (photoadaptation and chromatic adaptation) and the dimensions of phytoplankton cells in the water bodies. This gives rise to various wavelengths at which the short-wave maximum associated with chlorophyll *a* (ca 440 nm) occurs, modified by a range of smaller local peaks due to other forms of chlorophyll and carotenoids. In the middle part of the spectrum (550–650 nm) spectra of $a_{ph}^{*}(\lambda)$ are variously affected by phycobilin pigments, mainly phycoerythrin (ca 560 nm), allophycocyanin (ca 650 nm) and phycocyanin (ca 615 nm), which implies that cyanobacteria or red algae may be present in the water (Jeffrey and Vesk, 1997; Zhao et al., 2011). The relatively small differentiation of $a_{ph}^{*}(\lambda)$ in the red region of the spectrum is due to the conclusive influence of chlorophyll *a* on the overall absorption of light in this region, which is responsible for the conspicuous absorption peak for wavelength 675 nm. Other pigments (except for certain phycobilins and to a small extent chlorophyll *b*) practically do not absorb in this region. The differences in the long-wave absorption band are thus not caused by changes in the phytoplankton pigment content. It is assumed that different values of $a_{ph}^{*}(\lambda)$ in this band are due mainly to the packaging effect (Bricaud et al., 1995; Morel and Bricaud, 1981).

The dependence of the specific coefficient of absorption on the chlorophyll *a* concentration for the water bodies we have been discussing in this paper was empirically validated. Table 4 lists the accuracy of the formulas for calculating $a_{ph}^{*}(\lambda)$ using the relationship derived in this study (Eq. (4), Table 3). The estimation errors of $a_{ph}^{*}(\lambda)$ were also calculated

Table 4 Statistical and systematic errors of specific coefficients of light absorption by phytoplankton a_{ph}^{*}, calculated using Eq. (4) for coefficients $A(\lambda)$ and $B(\lambda)$ listed in Table 3 and Tables A1 and A2 – estimation and validation.

Parameterization	λ [nm]	Arithmetic statistics		Logarithmic statistics			
		Systematic error $\langle\varepsilon\rangle$ [%]	Statistical error σ_{ε} [%]	Systematic error $\langle\varepsilon\rangle_g$ [%]	Standard error factor x	Statistical error	
						σ_+ [%]	σ_- [%]
Estimation							
This study – all data	440	5.22	34.79	−0.09	1.38	37.92	−27.49
	500	6.59	39.77	0.12	1.42	42.05	−29.60
	600	7.39	40.92	0.20	1.46	45.77	−21.40
	675	4.18	29.63	0.18	1.33	32.59	−24.58
Baltic	440	4.95	33.53	−0.03	1.37	36.62	−26.80
	500	5.15	34.52	−0.15	1.38	38.05	−27.56
	600	6.33	39.81	−0.60	1.45	45.13	−31.09
	675	3.81	28.09	0.14	1.31	31.24	−23.81
Lakes	440	6.20	37.76	−0.06	1.42	42.47	−29.81
	500	8.75	45.77	−0.12	1.52	52.07	−34.24
	600	7.88	42.36	0.25	1.48	47.81	−32.35
	675	4.73	31.36	0.28	1.35	34.78	−25.81
Validation							
This study – all data	440	23.79	82.25	13.60	1.47	46.76	−31.86
	500	40.04	98.27	27.76	1.49	48.85	−32.82
	600	28.61	89.19	14.97	1.57	57.05	−36.32
	675	18.65	69.97	10.48	1.42	42.24	−26.69
Baltic	440	28.23	85.66	17.77	1.46	46.32	−31.66
	500	44.05	100.51	31.83	1.49	48.78	−32.79
	600	31.63	90.18	18.30	1.55	55.24	−35.59
	675	23.06	72.87	14.62	1.42	42.18	−29.67
Lakes	440	−19.24	24.26	−22.38	1.34	34.24	−25.50
	500	−13.70	34.37	−18.99	1.44	43.73	−30.43
	600	−23.70	13.53	−24.85	1.20	20.40	−16.94
	675	−16.76	20.98	−19.02	1.28	27.66	−21.66

Where $\epsilon = (X_{cal} - X_m)/X_m$ – arithmetic error; $\langle\varepsilon\rangle$ – mean arithmetic error; σ_{ε} – standard deviation (statistical error); $\langle\epsilon\rangle_g = 10^{[\langle\log(X_{i,cal}/X_{i,m})\rangle]} - 1$ – mean logarithmic error; $\langle\log(X_{i,cal}/X_{i,m})\rangle$ – mean of $\log(X_{i,cal}/X_{i,m})$; $\sigma_{\log}$ – standard deviation of $\log(X_{cal}/X_m)$; $x = 10^{\sigma_{\log}}$ – standard error factor; $\sigma_+ = x - 1$ i $\sigma_- = \frac{1}{x} - 1$.

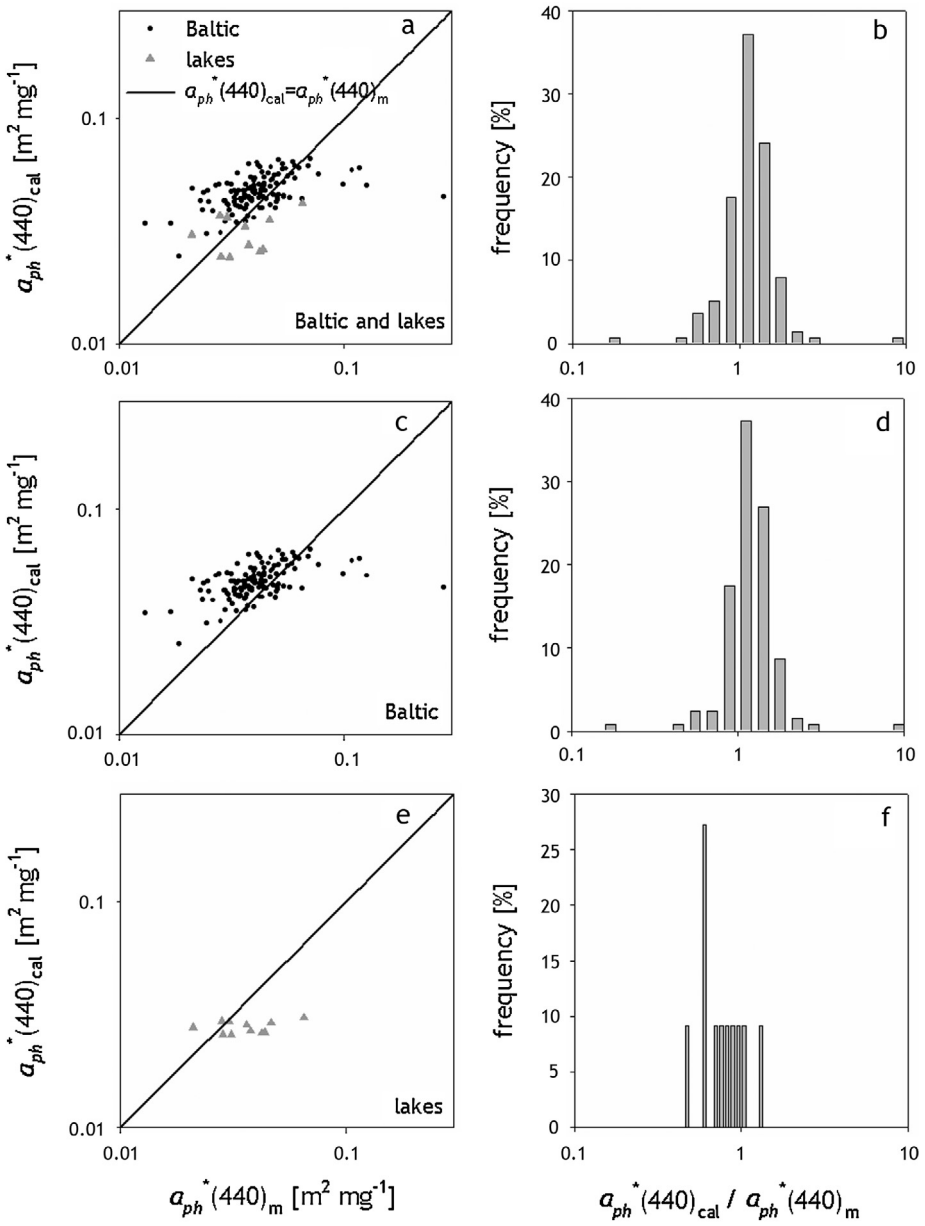

Figure 9 Validation using an independent dataset of measured light absorption coefficients for all suspended particles $a_{ph}(440)_m$ with those calculated $a_{ph}(440)_{cal}$ using Eq. (4) (left-hand column), and the probability density distribution of their ratio when the formulas are applied (right-hand column): (a and b) for all the data, (c and d) for Baltic data, (e and f) for lake data.

using an independent dataset. This contained data from lakes other than those explored in this study and from five cruises on the Baltic in 2011 (the variability ranges of *Chla* are shown in Table 1). The results of these analyses are presented in Fig. 9a–f for 440 nm, the wavelength at which absorption properties display their greatest variability.

Table 5 gives the errors obtained when other parameterizations are used to describe the waters in the study area. To this end, the values measured in these waters were compared with those calculated using the parameterizations described by various authors for four wavelengths. Statistical analysis showed that the parameterization derived in the present study yields the best estimate of $a_{ph}^*(\lambda)$ for Baltic Sea waters and the three Pomeranian lakes. This is endorsed by both the systematic errors and the standard error factors, which are lower than when the other parameterizations are applied. In this case the systematic error is from −55% to +54% (see Table 5), whereas when using the dependence derived for these waters, the error is <0.2%. Validation of the parameterization carried out in this work on an independent dataset shows that $a_{ph}^*(\lambda)$ was overestimated by 10–28% for all data (Baltic and lakes combined).

Table 5 Statistical and systematic errors of specific coefficients of light absorption by phytoplankton a_{ph}^{*}, calculated using parameterizations derived by other authors.

Parameterization	λ [nm]	Arithmetic statistics		Logarithmic statistics			
		Systematic error $\langle\varepsilon\rangle$ [%]	Statistical error σ_ε [%]	Systematic error $\langle\varepsilon\rangle_g$ [%]	Standard error factor x	Statistical error	
						σ_+ [%]	σ_- [%]
Bricaud et al. (1995)	440	−51.51	17.09	−54.55	1.45	44.81	−30.94
	500	−47.08	19.61	−50.54	1.45	45.16	−31.11
	600	−39.67	22.93	−43.79	1.47	46.69	−31.83
	675	−36.76	17.89	−39.28	1.34	33.73	−25.22
Ficek et al. (2012a)	440	−11.90	31.56	−16.88	1.40	40.23	−28.69
	500	−27.23	30.64	−32.36	1.45	45.16	−31.11
	600	20.20	45.87	12.14	1.46	45.78	−31.40
	675	−13.38	26.59	−17.07	1.34	34.15	−25.46
Reinart et al. (2004)	440	−28.78	28.15	−34.64	1.55	54.58	−35.31
	500	−28.41	29.70	−34.71	1.56	56.44	−36.08
	600	−12.73	33.43	−18.86	1.48	47.75	−32.32
	675	−49.06	16.24	−51.85	1.42	42.01	−29.58
Stæhr and Markager (2004)	440	−20.78	26.21	−24.95	1.39	39.46	−28.29
	500	−9.22	33.42	−14.72	1.42	42.29	−29.72
	600	−11.83	33.71	−17.98	1.48	47.51	−32.21
	675	−14.37	24.19	−17.75	1.34	33.54	−25.12
Yoshimura et al. (2012)	440	14.60	37.64	8.77	1.38	38.40	−27.75
	500	35.46	49.75	27.22	1.42	42.44	−29.79
	600	44.77	55.25	34.72	1.47	47.29	−32.11
	675	16.74	33.04	12.27	1.33	32.63	−24.60
Ylöstalo et al. (2014)	440	−30.58	22.79	−34.10	1.38	38.25	−27.67
	500	−30.15	26.75	−34.49	1.42	42.35	−29.75
	600	−18.01	31.56	−23.56	1.46	45.96	−31.49
	675	−28.02	20.30	−30.79	1.33	32.78	−24.69
Paavel et al. (2016)	440	−18.83	28.20	−23.20	1.39	39.12	−28.12
	500	−44.54	28.38	−49.82	1.54	53.87	−35.01
	600	67.70	67.78	54.01	1.54	53.51	−34.86
	675	7.51	31.42	2.77	1.36	36.24	−26.60

4. Conclusions

This paper analyses an extensive set of phytoplankton absorption spectra from the southern Baltic Sea and Pomeranian lakes as well as their corresponding chlorophyll *a* concentrations. As a result, we have been able to:

1. confirm the similarity of the optical properties, assumed earlier (Ficek, 2013; Le et al., 2009), between coastal lakes, which are influenced by the marine environment, and the nearby marine waters strongly affected by the terrestrial factor;
2. justify the construction of local algorithms enabling the optical properties of water bodies to be determined on the basis of known concentrations of their constituents;
3. establish a relationship enabling one to calculate with satisfactory accuracy the specific coefficient of light absorption by phytoplankton in the waters of both the Baltic Sea and Pomeranian lakes based on a knowledge of just the chlorophyll *a* concentration.

The validation of these relationships (on an independent set of empirical data) shows that they are applicable in monitoring studies, whenever a quick, approximate assessment of light absorption spectra is needed. This is confirmed by the errors of such approximations (systematic error in the 8.25%–32% range, and the error factor x in the 1.42–1.59 range).

The results of this analysis of the variability of specific coefficients of light absorption by phytoplankton cells and by CDOM (see the parameterizations presented in Meler et al., 2016b) in the waters of the Baltic Sea and some Pomeranian lakes have expanded our knowledge of their optical properties and contributed to the development of remote methods of determining their bio-optical characteristics (Darecki et al., 2003, 2008; Woźniak, 2014). The use of local dependences in *remote sensing* techniques can significantly improve their accuracy.

For example, the model presented in this paper for calculating $a_{ph}^{*}(\lambda)$ from known *Chla* can be used to test the products of the OCLI meter for the Baltic Sea, once they have been made public. These relationships can also be applied to the *remote sensing* algorithms used to calculate the concentrations of various sea water constituents, replacing the constant, wavelength-independent absorption coefficients used hitherto (Darecki et al., 2003; Kutser, 1997, 2004; Kutser

et al., 2001). Our analyses can also be applied to QAA (Quasi-Analytical Algorithm) inversion (Lee et al., 2002).

In order to obtain a more accurate description of the absorption properties of phytoplankton, every analysis has to allow for changes in the phytoplankton species composition, which is intimately associated with the environmental conditions prevailing in a given water body. The packaging effect also has a variable influence, significantly affecting light absorption coefficients of phytoplankton. A number of other factors affecting absorption properties, such as the season when or the area where observations are being made, also have to be taken into consideration. If this is done, multi-component models can be constructed that are much more complex and require knowledge of input data, the acquisition of which is much more time- and labor-consuming than the chlorophyll *a* concentration, which can be remotely sensed. Such complex models are therefore inappropriate for monitoring use. It is also more difficult to apply them in *remote sensing* (including satellite) algorithms for investigating the waters of the southern Baltic coast and Pomeranian lakes.

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Appendix

Tables A1 and A2.

Table A1 Values of parameters $A(\lambda)$ [m^2 mg^{-1}] and $B(\lambda)$ [dimensionless] obtained in the southern Baltic by fitting the variability of $a_{ph}^*(\lambda)$ with respect to *Chla*, in accordance with Eq. (4) for the 400—700 nm range, with a 5 nm step.

λ [nm]	*A*	*B*	λ [nm]	*A*	*B*	λ [nm]	*A*	*B*
1	2	3	1	2	3	1	2	3
400	0.0464	0.161	505	0.0297	0.178	610	0.0086	0.103
405	0.0492	0.165	510	0.0266	0.175	615	0.009	0.097
410	0.0525	0.171	515	0.0238	0.175	620	0.0094	0.089
415	0.0553	0.175	520	0.02016	0.177	625	0.0096	0.085
420	0.0571	0.181	525	0.0199	0.178	630	0.0098	0.086
425	0.0586	0.186	530	0.0185	0.175	635	0.0101	0.095
430	0.0606	0.191	535	0.0174	0.172	640	0.0104	0.103
435	0.0622	0.195	540	0.0165	0.172	645	0.0106	0.106
440	0.0612	0.194	545	0.0156	0.175	650	0.0111	0.103
445	0.0579	0.193	550	0.0148	0.177	655	0.0123	0.094
450	0.0539	0.192	555	0.014	0.185	660	0.0154	0.094
455	0.0514	0.196	560	0.0132	0.191	665	0.02	0.101
460	0.0501	0.201	565	0.0126	0.197	670	0.0244	0.109
465	0.049	0.204	570	0.0121	0.196	675	0.0264	0.113
470	0.0471	0.205	575	0.0114	0.184	680	0.0248	0.114
475	0.045	0.206	580	0.0103	0.159	685	0.0193	0.102
480	0.0426	0.204	585	0.0098	0.147	690	0.0124	0.084
485	0.0406	0.2	590	0.0093	0.129	695	0.0071	0.07
490	0.0386	0.195	595	0.0089	0.126	700	0.0041	0.07
495	0.036	0.188	600	0.0085	0.121			
500	0.0329	0.182	605	0.0084	0.11			

Table A2 Values of parameters $A(\lambda)$ [m^2 mg^{-1}] and $B(\lambda)$ [dimensionless] obtained in lakes by fitting the variability of $a_{ph}^*(\lambda)$ with respect to *Chla*, in accordance with Eq. (4) for the 400—700 nm range, with a 5 nm step.

λ [nm]	*A*	*B*	λ [nm]	*A*	*B*	λ [nm]	*A*	*B*
1	2	3	1	2	3	1	2	3
400	0.0436	0.136	505	0.0149	0.085	610	0.0097	0.081
405	0.0428	0.127	510	0.0138	0.092	615	0.0106	0.089
410	0.0434	0.122	515	0.0131	0.104	620	0.0103	0.069
415	0.0439	0.12	520	0.0129	0.124	625	0.01	0.057
420	0.0411	0.102	525	0.0125	0.135	630	0.01	0.058
425	0.0381	0.084	530	0.0119	0.142	635	0.0095	0.047
430	0.0365	0.072	535	0.0113	0.144	640	0.0089	0.033
435	0.0355	0.064	540	0.0109	0.147	645	0.0086	0.02
440	0.0346	0.064	545	0.0105	0.154	650	0.0086	0.008
445	0.0325	0.067	550	0.0102	0.162	655	0.009	−0.0058
450	0.0301	0.081	555	0.01	0.167	660	0.0106	−0.0105
455	0.0275	0.09	560	0.0098	0.167	665	0.0123	−0.0221
460	0.0249	0.088	565	0.0095	0.156	670	0.0136	−0.0327
465	0.0226	0.077	570	0.0097	0.15	675	0.0137	−0.0433
470	0.0208	0.07	575	0.0102	0.149	680	0.0123	−0.0589
475	0.0193	0.065	580	0.0101	0.134	685	0.0102	−0.064
480	0.0182	0.061	585	0.0101	0.123	690	0.0079	−0.0447
485	0.0172	0.06	590	0.0105	0.128	695	0.0056	−0.0214
490	0.0169	0.066	595	0.0104	0.122	700	0.0039	0.01
495	0.0165	0.072	600	0.0097	0.102			
500	0.0158	0.078	605	0.0095	0.091			

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