Oceanologia (2017) 59, 195—212

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.journals.elsevier.com/oceanologia/

ORIGINAL RESEARCH ARTICLE

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

Justyna Meler [a,*], Mirosława Ostrowska [a], Dariusz Ficek [b], Agnieszka Zdun [a]

[a] Institute of Oceanology, Polish Academy of Sciences, Sopot, Poland
[b] Institute of Physics, Pomeranian University, Słupsk, Poland

Received 12 September 2016; accepted 27 March 2017
Available online 19 April 2017

KEYWORDS
Baltic Sea;
Pomeranian lakes;
Parameterization of phytoplankton absorption

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%).

* Corresponding author at: Institute of Oceanology, Polish Academy of Sciences, Sopot, Poland. Tel.: +48587311807.
E-mail address: jmeler@iopan.pl (J. Meler).
Peer review under the responsibility of Institute of Oceanology of the Polish Academy of Sciences.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.oceano.2017.03.010

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