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ORIGINAL RESEARCH ARTICLE

Laboratory measurements of remote sensing reflectance of selected phytoplankton species from the Baltic Sea

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Summary Results of unique laboratory measurements of remote sensing reflectance (R_{rs}) of several phytoplankton species typically occurring in high abundances in the Baltic Sea waters are presented. Reflectance spectra for diatoms: *Cyclotella meneghiniana* and *Skeletonema marinoi* and cyanobacteria: *Dolichospermum* sp., *Nodularia spumigena* and *Synechococcus* sp. were analysed in terms of assessment of their characteristic features and the differences between them. These species contain similar pigments, which results in general similarities of reflectance spectra, i.e. decrease of reflectance magnitude in the blue and red spectrum regions. However, hyper-spectral resolution of optical measurements let us find differences between optical signatures of diatoms and cyanobacteria groups and between species belonging to one group as well. These differences are reflected in location of local maxima and minima in the reflectance spectrum and changes in relative height of characteristic peaks with changes of phytoplankton concentration. Wide ranges of phytoplankton concentrations were analysed in order to show the persistence of R_{rs} characteristic features. The picoplankton species, *Synechococcus* sp. show the

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most distinct optical signature, which let to distinguish separate cluster in hierarchical cluster analysis (HCA). The results can be used to calibrate input data into radiative transfer model, e.g. phase function or to validate modelled R_{rs} spectra.

1. Introduction

Harmful algal blooms that can vary in terms of their harmfulness, causal organisms, biomass distribution, and many other factors affecting the marine environment occur frequently in many marine and freshwater reservoirs. In the Baltic Sea massive phytoplankton blooms affecting its entire ecosystem are observed almost every year during spring, summer and early autumn (Kahru, 1997; Klais et al., 2013; Kutser et al., 2006; Pliński et al., 2007). From this point of view monitoring of these blooms, especially with cost effective methods like optical indirect measurements carried out in situ or remotely, e.g. by satellites, is in the interest of many environmental agencies and institutions. There is a strong demand for remote sensing algorithms which enable distinguishing between different phytoplankton species (IOCCG, 2014; Sathyendranath et al., 2016). Some of published studies use look up tables (LUT) (Xi et al., 2015) or optical indexes (Kim et al., 2016) based on modelled R_{rs} characteristics for individual species, but output of these models has not been validated against measured R_{rs}. The results presented here can be a significant contributions to that goal.

The spectral characteristic of the water leaving radiance (L_w) can be linked to the optically significant components of seawater. Thus the spectra of remote sensing reflectance (R_{rs}), being the ratio between the upwelling radiance just above the water and the downwelling irradiance at the sea surface, can be a useful tool which relates optical measurements to desired optically active seawater constituents (e.g. Darecki et al., 2008; Kratzer et al., 2008; Soja-Woźniak et al., 2017; Woźniak et al., 2008). For last two decades both in situ and remote sensing radiometry has developed significantly. Improved in situ techniques enabled measurement of L_w with hyperspectral resolution while bio-optical studies gave increasingly better understanding of the interaction between water components and the light field (Evers-King et al., 2014). Nowadays, retrieval of the phytoplankton pigments concentration based on R_{rs} can be obtained with reasonable accuracy (Darecki and Stramski, 2004; Darecki at al., 2008; Simis et al., 2005; Soja-Woźniak et al., 2017; Woźniak et al., 2016), but identification of single phytoplankton species or even entire phytoplankton functional groups by means of R_{rs} still remains a challenge (Craig et al., 2006; Hunter et al., 2008; Lubac et al., 2008; Shang et al., 2014; Torrecilla et al., 2011; Xi et al., 2015).

Phytoplankton species are characterised by their unique light absorption and backscattering properties resulting from differences in cell sizes and shapes, inner structure and composition of the pigments (e.g. Aguirre-Gómez et al., 2001; Vaillancourt et al., 2004; Whitmire et al., 2010) that all influence the shape of the R_{rs} spectra. The main pigments occurring in cyanobacteria and diatoms together with their absorptive properties are given in Table 1. Analysis of remote sensing reflectance of the Baltic Sea phytoplankton was carried out in the previous studies in order to detect and characterise algal blooms and to differentiate phytoplankton taxonomic groups (e.g. Kutser et al., 2006; Xi et al., 2015). However, the R_{rs} has been determined using either the R_{rs} dependence on the absorption and backscattering given by Gordon et al. (1975) or radiative transfer simulations. This approach can lead to some errors resulting from the applied assumptions, e.g. the assumption of the shape of the scattering function which for the phytoplankton cultures can be much different from the average Petzold particle scattering function as shown by Volten et al. (1998). There have been several studies performed in which the R_{rs} spectra of various phytoplankton taxonomic were measured under controlled laboratory or semi-laboratory conditions (Table 2).

Table 1 Main pigments occurring in cyanobacteria and diatoms with the location of main absorption peaks (based on Roy et al., 1989). The "+" sign indicates the presence of the chosen pigment.

Pigment	Cyanobacteria	Diatoms	Location of main absorption peaks [nm]
Chlorophylls			
a	+	+	430–432, 662–666
c		+	442–457, 628–634
Carotenoids			
β-Carotene	+	+	451–454, 475–480
Myxoxanthophyll	+		472–478, 502–510
Zeoxanthin	+		449–454, 475–481
Diadinoxanthin		+	445–449, 475–479
Diatoxanthin		+	451–453, 478–480
Fucoxanthin		+	444–449, 467–475
Phycobilins			
Phycocyanin	+		620
Phycoerythrin	+		550
Allophycocyanin	+		650

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