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ORIGINAL RESEARCH ARTICLE

Testing the performance of empirical remote sensing algorithms in the Baltic Sea waters with modelled and *in situ* reflectance data

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Summary Remote sensing studies published up to now show that the performance of empirical (band-ratio type) algorithms in different parts of the Baltic Sea is highly variable. Best performing algorithms are different in the different regions of the Baltic Sea. Moreover, there is indication that the algorithms have to be seasonal as the optical properties of phytoplankton assemblages dominating in spring and summer are different. We modelled 15,600 reflectance spectra using HydroLight radiative transfer model to test 58 previously published empirical algorithms. 7200 of the spectra were modelled using specific inherent optical properties (SIOPs) of the open parts of the Baltic Sea in summer and 8400 with SIOPs of spring season. Concentration range of chlorophyll-*a*, coloured dissolved organic matter (CDOM) and suspended matter used in the model simulations were based on the actually measured values available in literature. For each optically active constituent we added one concentration below actually measured minimum and one concentration above the actually measured maximum value in order to test the performance of the algorithms in wider range. 77 *in situ* reflectance spectra from rocky (Sweden) and sandy

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(Estonia, Latvia) coastal areas were used to evaluate the performance of the algorithms also in coastal waters. Seasonal differences in the algorithm performance were confirmed but we found also algorithms that can be used in both spring and summer conditions. The algorithms that use bands available on OLCI, launched in February 2016, are highlighted as this sensor will be available for Baltic Sea monitoring for coming decades.

1. Introduction

Water reflectance data collected with field radiometers has mainly been used for satellite data calibration and validation purposes. However, handheld devices and portable autonomous systems on ferries, jetties, and buoys have become remote sensing tools in their own, as they allow collecting fast and frequent data about the state of waterbodies (Alikas et al., 2015; Groetsch et al., 2014; Simis and Olsson, 2013). Processing the radiometer, as well as satellite data, can be carried out in different ways. A "classical" approach is developing empirical relationships between band-ratios (colour indices), their combinations or more sophisticated parameters and water characteristics, like chlorophyll-*a* concentration. The disadvantages of the empirical methods are that they tend to be local (need tuning for a particular waterbody) or even seasonal (Metsamaa et al., 2006), and need to be developed for each sensor used.

An alternative approach is physics-based analytical methods, where full modelled spectra are used for retrieving chlorophyll-*a*, suspended matter and CDOM (coloured dissolved organic matter) are becoming more and more popular in interpretation of aquatic remote sensing data. Such methods have also been used for more than two decades (Arst and Kutser, 1994; Kutser et al., 2001) and advanced to inversion procedures like Sambuca (Dekker et al., 2011), Bomber (Giardino et al., 2012) retrieving inherent optical water properties (IOPs) and shallow water bottom type simultaneously. There are also neural network type approaches like the method developed for MERIS (Doerffer and Schiller, 2007). The disadvantages of analytical methods, that use water leaving reflectance as the source for water quality parameters calculations, are that they are computationally expensive and require very high-quality input data (*e.g.* perfect atmospheric correction) that is often difficult to achieve. The requirement of high quality input data refers to the spectral library and other model inversion methods. Neural networks can be trained to produce reasonable results even if the reflectance spectra are unrealistic.

It has been shown by many authors (Beltran-Abaunza et al., 2014; Darecki and Stramski, 2004; Kratzer et al., 2008; Reinart and Kutser, 2006) that ocean colour algorithms based on the ratio of blue and green bands (like the OC4v6 developed for retrieving chlorophyll-*a*) provided by different space agencies do not perform well in such optically complex waterbodies like the Baltic Sea. There have been remote sensing activities in different parts of the Baltic Sea and variety of empirical algorithms have been proposed (Attila et al., 2013; Beltran-Abaunza et al., 2014; Darecki et al., 2003, 2005, 2008; Härmä et al., 2001; Koponen et al., 2007; Kowalczuk et al., 2005a, 2010; Kutser, 2004; Kutser et al., 2005a, 2006; Woźniak et al., 2008). However, the algorithms proposed are usually local; applying them in other parts of the sea requires tuning of the algorithms. Moreover, previous studies suggested that there may be need for seasonal water quality algorithms in the Baltic Sea as phytoplankton assemblages in spring and summer are different and their optical properties are very different (Erm et al., 2008; Feistel et al., 2008; Kowalczuk et al., 2005b; Wasmund and Uhlig, 2003). This means that, on the one hand, creating the spectral library necessary for retrieving water properties in the Baltic Sea has to contain reflectance spectra for different seasons. On the other hand, it also suggests that it may be difficult to find band-ratio type algorithms that perform well during the whole year.

As seen in the MERIS ATBD (Doerffer and Schiller, 1997), neural networks have several complicated steps in their calculation. Therefore, the computations may take time, when large satellite images are processed. Empirical algorithms can be used to define initial values for analytical processing to speed up the process by narrowing down the range of variation. For example, the inversion procedures do not have to use the whole spectral library, but only parts of it when approximate concentrations of chlorophyll-*a*, CDOM and suspended matter have been estimated by band-ratio type algorithms. Many satellite instruments are configured to measure water-leaving signal only at a few spectral bands. It means that analytical methods are not always easily usable in interpretation of data from such sensors. Simple band-ratio type remote sensing algorithms are often a good option for retrieving water quality parameters from multispectral data, but these algorithms may also be used in the case of sensors with better spectral resolution as they are computationally fast and easy to use. Therefore, these computationally simple algorithms are also widely used in remote sensing (Ammenberg et al., 2002; Gitelson et al., 2009; Kallio et al., 2001; Koponen et al., 2007).

Our aim was to test whether there are simple empirical algorithms, that use only few spectral channels, which allow estimating chlorophyll-*a*, CDOM and suspended matter concentrations in the Baltic Sea. In an ideal case these algorithms should work all year round, but finding even seasonal algorithms that perform well would be a step forward. The tested algorithms were taken from previously published papers. The reflectance data used in this study was partly simulated with HydroLight radiative model using both summer and spring sets of SIOPs. The concentrations of chlorophyll-*a*, suspended matter and CDOM used in the model simulations covered the whole known range for the Baltic