Oceanologia (2016) 58, 161—175

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/oceano

ORIGINAL RESEARCH ARTICLE

New simple statistical formulas for estimating surface concentrations of suspended particulate matter (SPM) and particulate organic carbon (POC) from remote-sensing reflectance in the southern Baltic Sea☆

Sławomir B. Woźniak [a,*], Mirosław Darecki [a], Monika Zabłocka [a], Dorota Burska [b], Jerzy Dera [a]

[a] *Institute of Oceanology, Polish Academy of Sciences, Sopot, Poland*
[b] *Institute of Oceanography, University of Gdańsk, Gdynia, Poland*

Received 8 January 2016; accepted 25 March 2016
Available online 15 April 2016

KEYWORDS
Remote-sensing reflectance;
Light backscattering;
Suspended particulate matter;
Particulate organic carbon;
Empirical formulas;
Southern Baltic surface water

Summary In a step taken towards improving the new system for the satellite monitoring of the Baltic Sea environment, officially started in Poland recently (*SatBałtyk System*, see http://www.satbaltyk.pl), a new set of simple statistical formulas was derived. These combine the empirically determined spectral values of remote-sensing reflectance $R_{rs}(\lambda)$ with the mass concentrations of suspended particulate matter (SPM) and particulate organic carbon (POC) in southern Baltic surface waters. The new formulas are based on 73 empirical data sets gathered during 4 research cruises on board r/v *Oceania* during spring and late summer in the open waters of the southern Baltic and coastal regions of the Gulf of Gdańsk. Correlations of SPM and POC concentrations with reflectance or reflectance ratios in various spectral bands were tested. Several variants of candidate statistical relationships, which can be used later in the construction of simple local remote sensing algorithms for the waters in question, are introduced here. These relationships utilise either absolute values of R_{rs} at a selected waveband, mostly from the yellow, red or near

☆ Financial support for this research was provided by the 'SatBałtyk' project funded by the European Union through the European Regional Development Fund (contract No. POIG.01.01.02-22-011/09 entitled 'The Satellite Monitoring of the Baltic Sea Environment'), and by Statutory Research Programme at the Institute of Oceanology, Polish Academy of Sciences (themes No. I.1 and II.5).
* Corresponding author at: Institute of Oceanology, Polish Academy of Sciences, Powstańców Warszawy 55, 81-712 Sopot, Poland. Tel.: +48 58 7311812.
E-mail address: woznjr@iopan.gda.pl (S.B. Woźniak).
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.2016.03.002

infrared part of the light spectrum, or R_{rs} ratios for two different wavebands, mostly ratios of blue to yellow, blue to red and blue to infrared or green to yellow and green to red spectral band. From the numerous simple approximate relationships established, the following two, characterised by large correlation coefficients r^2 and small standard error factors X, may serve as examples: SPM [g m^{-3}] = $1480(R_{rs}(710))^{0.902}$ (with the factors $r^2 = 0.86$; $X = 1.26$) (the unit of $R_{rs}(\lambda)$ is [sr^{-1}]) and POC [g m^{-3}] = $0.814(R_{rs}(555)/R_{rs}(589))^{-4.42}$ ($r^2 = 0.75$; $X = 1.37$). From the practical standpoint, taking into consideration light wavelengths that are close to or concurrent with the currently available spectral bands used in satellite observations of the Baltic Sea, another two formulas (using the same spectral ratio) are worth pointing out: SPM [g m^{-3}] = $2.6(R_{rs}(490)/R_{rs}(625))^{-1.29}$ ($r^2 = 0.86$; $X = 1.25$) and POC [g m^{-3}] = $0.774(R_{rs}(490)/R_{rs}(625))^{-1.18}$ ($r^2 = 0.66$; $X = 1.44$). The paper also presents a number of intermediate statistical relationships between SPM and POC concentrations, R_{rs} spectra and light backscattering coefficients in order to illustrate the simplified physical justification for some of the observed direct statistical relationships, presented as the main content of this work.

1. Introduction

In recent decades there has been significant progress in passive remote-sensing techniques that retrieve information on seawater composition imprinted in the colour of oceans and seas (see, for example, a series of reports by International Ocean-Colour Coordination Group — IOCCG Report 16 (2015) or earlier reports and the references cited therein). To make full use of the potential of these techniques, there is obviously a need to mathematically relate the quantity that describes sea colour precisely, i.e. the remote-sensing reflectance, with the various biogeochemical characteristics describing the concentrations and composition of substances present in surface waters. In practice this can be done in many ways, either directly or indirectly by using the water's inherent optical properties (IOPs) as a “link” between the sea's colour and biogeochemistry. One of the biogeochemical characteristics most often studied with remote sensing techniques is the concentration of chlorophyll *a*, the quantity used as the basic measure of phytoplankton biomass. Other substances that are also important indicators of different processes taking place in seawater and at the same time influence its colour include phytoplankton pigments other than chlorophyll *a*, chromophoric dissolved organic matter (CDOM), suspended particulate matter (SPM) of both organic and inorganic origin, and the main chemical elements from which organic matter is constructed, e.g. carbon. Hence it is mainly the relationships between the concentrations of these substances/elements and the remote-sensing reflectance, often specific to particular seas, that are investigated.

The application of remote-sensing techniques in the Baltic region started in the 1970s (when the first oceanographic satellites became available) and has intensified in the last 20 years. This problem has been addressed by different scientific groups from many countries, not just from states around the Baltic Sea (detailed literature surveys on this topic can be found, for example, in book chapters by Siegel and Gerth (2008), Berthon et al. (2008) or Kratzer et al. (2011); see also Arst (2003)). The brackish waters of the semi-enclosed shelf basin of the Baltic Sea are optically very complex. These waters belong to a broad category of Case 2 waters (according to the classification of Morel and Prieur (1977)), the optical properties of which do not depend only on phytoplankton and its by-products. In Case 2 waters an important role may be also played by suspended matter and CDOM, which generally do not co-vary with chlorophyll *a* concentration. Indeed, Baltic waters are an exceptional example of Case 2 waters, since they are much richer in both allogenic and autogenic CDOM than other shelf seas (see e.g. Kowalczuk (1999)). Consequently, optical relationships, models and algorithms derived as being either universal/global, or even local but for other marine environments, are often unsuitable for Baltic Sea remote sensing (see e.g. a work by Darecki and Stramski (2004), in which the performances of different chlorophyll *a* algorithms in the Baltic Sea are compared). The derivation of local algorithms thus appears to be indispensable. In the last 10 years or so, the application of neural network algorithms has become a common practical approach to the remote sensing of the Baltic and other European seas (see e.g. Doerffer and Schiller (2006)). Such algorithms use the artificial neural network inversion procedure to derive various independently varying in-water constituents, such as chlorophyll *a* (or pigment index), SPM and CDOM. The input for such algorithms is usually multispectral information (specific to the satellite sensors under consideration) on either top of atmosphere radiances or remote sensing reflectances. Recent evaluations and comparisons of different variants of such algorithms applied to Baltic data acquired using a medium resolution imaging spectrometer (MERIS) can be found, for example, in Beltran-Abaunza et al. (2014) or D'Alimonte et al. (2014). Another observation from the literature survey may be that particulate organic carbon (POC) has not yet become a common ocean colour data product for the Baltic Sea region, despite the already demonstrated fact that SPM can be treated as its effective tracer (Ferrari et al., 2003).

In common with many other scientific groups and institutions working on the optics of Baltic Sea waters, a group of scientists from Poland has also been deeply involved in this topic in recent decades (Dera and B. Woźniak, 2010 and the extensive list of citations therein). The Polish team has also undertaken comprehensive studies with the aim of developing