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ORIGINAL RESEARCH ARTICLE

Narrowband shortwave minima in spectra of backscattered light from the sea obtained from ocean color scanners as a remote indication of algal blooms[☆]

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Summary We propose a new approach to indication of algal blooms. It stems from analysis of the multispectral satellite reflectance R_{rs} of areas where blooms were documented during recent decades. We found that spectra of algal blooms exhibit minima at wavelengths of channels of Moderate Resolution Imaging Spectroradiometer (MODIS) $\lambda = 443$ and $\lambda = 488$ nm (Baltic, Black, and Caspian seas), $\lambda = 443$ nm (Southwest Tropical Pacific (SWTP)), and $\lambda = 443$ nm and $\lambda = 469$ nm (Patagonian Continental Shelf (PCS)), attributable to absorption bands of chlorophyll *a* and accessory pigments. We quantified the minima using indices $D1 = R_{rs}(443) - R_{rs}(412)$ and $D2 = R_{rs}(488) - R_{rs}(469)$ and proved their diagnostic potential by comparing their distributions to that of $R_{rs}(555)$. Linear dependence of D1 upon chlorophyll *a* was found from MODIS data for the bloom of *Nodularia spumigena*. Time dependences of D1 and D2 point to the latter as a probable remote forerunner of cyanobacterial blooms. In the PCS, D1 and D2 proved to be too simplistic owing to diversity of spectral shapes at $\lambda < 550$ nm. Cluster analysis revealed close linkage of the latter and local oceanological conditions. Our findings bear witness to the diagnostic potential of the indices by virtue of their direct relation to pigment absorption and because the broadband background reflectance changes reduce when calculating the indices as a difference of spectrally

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close reflectances. Further studies are needed to convert the indices to band-difference algorithms for retrieving the bio-optical characteristics of algal blooms.

1. Introduction

The rapid growth of microalgae abundance in water basins is usually referred to as algal bloom. Extensive studies of blooms during last decades revealed recurrence of blooms in many areas of the oceans (Anderson, 2001; Sellner et al., 2003). A bloom may be induced by a set or a single algal species. The blooms occur in different climatic zones and cover the areas sizing from local scales to basin-wide ones. The period, when algal cells concentration in water exceeds a certain threshold level, determines the lifetime of a bloom. This period lasts from days to months. Radical changes in content and composition of suspended particles, dissolved organic matter, nutrients and other substances accompany the blooms because of vital activity of the microorganisms, their lifetime excretions, consumption, degradation, and final decomposition. These processes develop against a background of water dynamics events of different scales, which contributing into the intricacy of bloom patterns. The necessity to understand the latter is particularly urgent because some of the algae produce toxins and induce the harmful algal blooms (HABs) dangerous for aquatic biota and humans (Sellner et al., 2003).

The understanding of such cause-and-effect relations requires knowing the distributions of the relevant organisms and substances in time and space on periods from seconds to years and on scales from 10^0 to 10^6 m. To date, the problem of 'undersampling' (Munk, 2002) is far from being eliminated in biological oceanography since the labor-consuming laboratory treatment of water samples for studying the ecologically significant objects remains relevant (Balzano et al., 2015). The light absorbing and fluorescing chlorophyll and accessory pigments are inherent to the algae, which provides great scope for rapid remote sensing of algal abundance in different aquatic environments. In their pioneering work, Clarke et al. (1970) used an airborne spectroradiometer for recording the spectra of solar radiation, backscattered from the Sargasso Sea and coastal waters. In authors' judgment, the shape of these spectra demonstrated much potential for yielding information about algal chlorophyll in the near surface layer in spite of the fact that there were no radiance minima attributable to the absorption of light by algal pigments. At present, these potentialities are implemented as a system of satellite instrumentation, techniques, band-ratio algorithms, and discoveries described in thousands of publications. It is precisely the satellite information of global coverage that underlies the present day knowledge of geography, duration, and scales of algal blooms and inhomogeneities of optically significant admixtures in the World Ocean (McClain, 2001; Świgoń and Stramska, 2015).

These successes were achieved thanks to orbiting multispectral ocean color scanners (OCSs) run by the NASA and ESA since 1978. Elimination of atmospheric contribution into the OCS products (atmospheric correction) makes them indispensable for ocean studies. The OCSs are distinguished by swaths more than 1000 km wide, ground sample distance (GSD) close to 1 km or less, and rated revisit time as short as 1—2 days which fits well to time and space scales of algal blooms. Such a consistency has been achieved at the expense of spectral resolution of the OCSs, which usually have several spectral bands in the visible range. This is insufficient for reliable identification of blooming algae from manifestation of individual absorption and fluorescence bands of algal chlorophyll and accessory pigments in the satellite reflectance spectra of the sea surface. At the same time, manifestations of this kind were occasionally reported in publications based on data of the shipborne hyperspectral radiometers.

When recording the R_{rs} spectra with a floating spectrometer in the Falkland Current frontal zone, Kopelevich et al. (2005) observed a broad minimum in the violet-blue range roughly at 440 nm where the absorption band of chlorophyll *a* belongs. This fact agrees well with information on blooms of various algae in the system of Falkland-Brazilian currents and the Patagonian Continental Shelf (Ferreira et al., 2013; Painter et al., 2010; Sabatini et al., 2012). Lubac and Loisel (2007) used a ship-borne spectrometer and recorded reflectance spectra having well-defined minimum in the blue-violet wavelength range. The minimum took place exclusively at stations in the English Channel where chlorophyll and cell counting in water samples provided evidence of the *Phaeocystis globosa* bloom. Similar shapes of the wavelength dependence of water-leaving radiance have been revealed by Soloviev (2005) when analyzing the images of the Caspian and Baltic Seas obtained with the OCS MODIS (Moderate Resolution Imaging Spectroradiometer) during blooms of *Nodularia spumigena* in summer 2005.

The MODIS determinations of sea surface reflectance have been improved in spectral resolution within the shortwave half of the visible spectrum upon data reprocessing version R2013.1. The updated estimates of R_{rs} are now available at the OceanColor website of NASA (http://oceancolor.gsfc.nasa.gov/) as Level 2 products at GSD = 1 km and wavelengths λ = 412, 443, 469, 488, 531, 547, 555, 645, 667, and 678 nm. Using the updated MODIS imagery for the same cyanobacterial bloom of 2005 in the Baltic Sea, we have found that better spectral resolution makes possible to discriminate the second shortwave reflectance minimum at 488 nm (Karabashev and Evdoshenko, 2015). Metsamaa et al. (2006) have measured the spectra of absorption coefficients of the cyanobacteria *Aphanizomenon flos-aquae* "*baltica*", *Anabaena circinalis* and *N. spumigena* as the main bloom-forming species in the Baltic Sea. In these organisms, the absorption of light peaks at 439 nm, exhibits weaker maximum at 479 nm, and tends to zero at 560 nm. The peak at 439 nm corresponds to the absorption maximum of the