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Satellite monitoring of coccolithophore blooms in the Black Sea from ocean color data

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ABSTRACT

Satellite observation is an eminently suitable tool for monitoring and study of coccolithophore blooms but quantitative estimation needs perfected algorithms. The current satellite algorithm using the data of ocean color scanners, such as SeaWiFS and MODIS, is based on retrieval of the backscattering coefficient and then estimation of the calcite concentration via an empirical relationship. The regional algorithm for the Black Sea is also an empirical relationship between the coccolithophore concentration and the particle backscattering coefficient, based on in situ measured data. The drawback of the both algorithms is that “non-coccolithophore” backscattering is not accounted for. This shortcoming is particularly significant for the Black Sea which is strongly influenced by river runoff.

We analyze the problem of taking into account the “non-coccolithophore” backscattering by using the integrated approach with the comprehensive data set including satellite data and optical, hydrological and biogeochemical parameters measured in situ in the eastern part of the Black Sea. The main result obtained is a new algorithm for retrieval of coccolithophore concentration in the Black Sea from satellite ocean color data. The algorithm is based on the two-parametric model of the particle backscattering coefficient, which takes into account both coccolithophore bloom and river runoff. Application of the new algorithm to satellite ocean color data in 1998–2011 gave an opportunity to separate the changes associated with the abovementioned factors. Several new interesting results were obtained. It was shown that coccolithophore blooms occupied only a part of the area with high values of the particle backscattering coefficient, and there were the years with no coccolithophore bloom in the Black Sea in June even though the high values of the particle backscattering coefficient were observed.

The other problems to be solved for improvement of the satellite algorithm, providing a quantitative assessment of the intensity of coccolithophore blooms in the Black Sea, were discussed.

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1. Introduction

Coccolithophores are single-celled algae with a spherical cell covered by disk-shaped coccoliths, composed of calcium carbonate, $CaCO_3$. Coccolithophore blooms (CB) can spread to vast areas in various oceans and seas, and have a significant impact on important physical and biogeochemical processes, in particular, the exchange of CO_2 between the ocean and the atmosphere, and global climate change (Thierstein & Young, 2004). The long-term flux of coccoliths to the ocean floor contributes to the formation of chalk and limestone rocks. Plated cells and detached coccoliths have a strong non-selective light scattering, that makes it possible to detect CB from satellite color scanner. Our work deals with the problem of quantitative estimates of CB on the satellite data and development of a regional algorithm for the Black Sea, where data on coccolithophore and coccolith concentrations are available from field measurements. The water-leaving radiance, recorded by satellite color scanner, is increasing dramatically in the Black Sea in June. In most cases, this is due to the CB, but a close relationship between the particle backscattering coefficient b_{bp}, calculated from satellite data, and the intensity of the CB is not always observed.

An example of a coccolithophore bloom in the Black Sea is given in Fig. 1; it is seen that the bright areas in Fig. 1A correspond to the high values of b_{bp} in Fig. 1B (the b_{bp} distribution was computed by the simplified algorithm described by Burenkov, Ershova, Kopelevich, Sheberstov, & Shevchenko, 2001).

Satellite studies of coccolithophore blooms in the Black Sea began with SeaWiFS ocean color data (Cokacar, Kubilay, & Oguz, 2001). The particle backscattering coefficient b_{bp} is a key parameter for quantitative assessment of the CB intensity; its value is derived from satellite data and then used for calculating the CB characteristics (http://optics.ocean.ru). The NASA SeaDAS software (http://oceancolor.gsfc.nasa.gov/seadas/) can derive calcite ($CaCO_3$) concentration (particulate inorganic carbon — PIC) with the merged 2-band and 3-band algorithm, default for all sensors (Gordon & Balch, 1999; Gordon et al., 2001).

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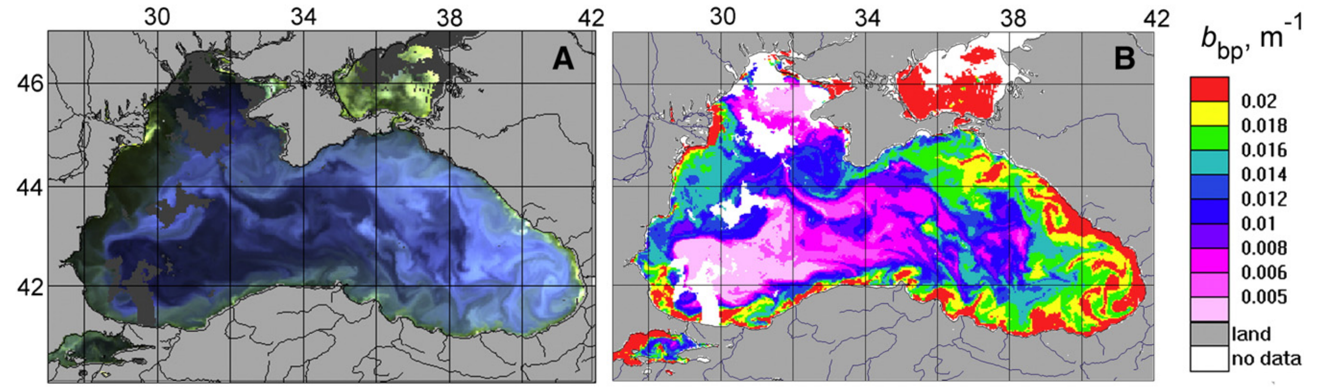

Fig. 1. Coccolithophore bloom in the Black Sea on 12 June 2004 from MODIS-Aqua satellite scanner. A, MODIS-Aqua image in true color; B, spatial distribution of the particle backscattering coefficient b_{bp}.

The obvious drawback of the above algorithm, which the authors themselves pointed out, is that all particulate backscatter is assumed to be calcite-related, and the non-calcite related backscattering is not taken into account. This shortcoming is particularly significant for the Black Sea which is strongly influenced by river run-off, and the concentration of particulate matter brought by rivers increases just in June, after the maximum of river discharge in the second half of May.

This inadequacy is also related to the SIO RAS algorithm for retrieval of coccolithophore concentration N_{coc} from satellite data on the particle backscattering b_{bp} (http://optics.ocean.ru). Our present study aims to take into account the "non-coccolithophore" backscattering in the Black Sea, using a new approach.

2. Data and methods

2.1. Study area

Our study is focused in the eastern part of the Black Sea, where the field measurements have been conducted since 2004. The Black Sea is classified with Case 2 waters because their seawater optical properties are determined not only by phytoplankton and by the material associated with it, as in Case 1 waters, but also by the particulate and dissolved matter brought with river runoff (International Ocean Color Coordinating Group (IOCCG), 2000). Based on the position, bathymetry and influence of river runoff, the Black Sea can be divided into eight sub-regions (Fig. 2).

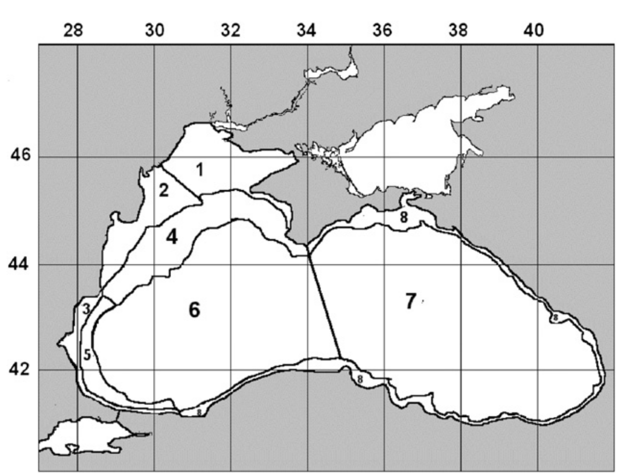

Fig. 2. Sub-regions in the Black Sea: 1 — northern inner shelf; 2 — north-western inner shelf; 3 — south-western inner shelf; 4 — north-western outer shelf; 5 — south-western outer shelf; 6 — western open part; 7 — eastern open part; and 8 — eastern and southern shelves.

Sub-regions #1–3 are located in the shelf area with depth of less than 50 m; region #1 is under strong influence of water discharge of the Dnieper, Dniester and Bug rivers, whereas region #2 is influenced mainly by the Danube River. Sub-regions #4 and 5 are the northern and southern areas of the outer shelf (depth of 50–200 m) in the western part of the Black Sea. In the eastern part of the basin, the southern, eastern and north-eastern shelf areas were considered as a single region (#8).

Though most large rivers (Danube, Dniester, Southern Bug, and Dnieper) flow into the Black Sea in the north-west (their suspended sediment load is equal to $41.5 \cdot 10^6$ t/year or about 55% of the total load), the contribution from the north-eastern, eastern and southern rivers of Russia, Georgia and Turkey is also high — $33.8 \cdot 10^6$ t/year altogether (Mikhailov, Morozov, Cheroy, Mikhailova, & Zavyalova, 2008). Their manifestation is well seen on satellite images in the second half of May and in June.

In 2004–2006, our field studies were conducted in both the coastal turbid and open clear waters; the stations were planned relying on the analysis of satellite data. The ship route in 2004 is shown on Fig. 3A.

As seen, the ship route included three sections: from Gelendjik to the open part (~44°N, 37.5°E), along the shore (to ~43°N, 38.5°E), and then from open sea to Sochi. The values of the bio-optical characteristics varied over a wide range: Secchi depth from 2.5 to 14 m, the near-surface beam attenuation coefficient from 0.4 to 3.4 m^{-1}, chlorophyll concentration from 0.17 to 0.65 mg m^{-3}, and suspended matter concentration from 0.5 to 4.1 mg/l.

Nearly the same values of the parameters were measured in expeditions in 2005–2006. In 2006, the ship route was planned for studying the area of turbid waters in open sea. In 2007–2011, by technical reason, we conducted our studies in the coastal zone.

2.2. Field studies

The field studies, in parallel with satellite observations, were carried out each June since 2004, to understand reasons of the enhanced values of b_{bp} in the eastern part of the Black Sea. They included optical and biogeochemical measurements. As a rule, the following optical quantities were measured: the upwelling radiance just beneath the sea surface and the surface irradiance by a floating spectroradiometer (Artemiev et al., 2000), the surface and underwater irradiance (Khrapko, Kopelevich, Burenkov, Grigoriev, & Terekhova, 2007), vertical distribution of the beam attenuation coefficient and seawater temperature by a submersible transmissometer, and Secchi depth. The biogeochemical parameters included the concentrations of chlorophyll "a" and pheophytin "a"

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