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Original article

Regional Coefficients for Calculating Suspended Matter Concentrations in the Black Sea Using Multi-Sensor Data

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Abstract
Purpose. The purpose of the study is to obtain quantitative estimates of regional coefficients for calculating the values of suspended matter concentrations in the surface layer of the northern and northeastern parts of the Black Sea based on a Quasi-Analytical Algorithm (QAA version 6) and daily multi-sensor data (SeaWiFS, MODIS, MERIS, VIIRS and OLCI) with spatial resolutions of 1 and 4 km.
Methods and Results. The paper presents *in situ* data on the values of mass concentration of suspended matter ≥ 0.2 μm in the surface layer of the northern and northeastern parts of the Black Sea obtained during the 138th cruise of the R/V *Professor Vodyanitsky* (November 14 – December 9, 2025). A total of 56 seawater samples were collected and processed at 56 stations. The volume of each sample pumped through a filter varied from 1.24 to 8.17 L and depended on the suspended matter content of the seawater. The backscattering coefficient values at 560 nm were calculated using multi-sensor (SeaWiFS, MODIS, MERIS, VIIRS and OLCI) data on the spectral radiance of the sea at spatial resolutions of 1 and 4 km and the Quasi-Analytical Algorithm (QAA version 6). The relationship between the above-mentioned coefficient and the suspended matter concentration was investigated. The study results made it possible to determine the values of regional coefficients in the linear regression equation that relates the backscattering coefficient to the suspended matter concentration.
Conclusions. In the area under study, the suspended matter concentration varied widely, from 0.17 to 1.48 mg/L. Higher values were observed near the Kerch Strait (1.2–1.48 mg/L) and Feodosia Gulf (0.9–1.2 mg/L). Lower values (0.17–0.55 mg/L) were characteristic of the deep part of the sea. The linear regression parameters relating the backscattering coefficient to the suspended matter concentration for the data with a 4-km resolution were 89.2 ± 6.3 (slope) and 0.24 ± 0.03 (intercept), and those for the data with a 1-km resolution were 102.6 ± 7.3 and 0.21 ± 0.03, respectively. A comparison of the calculated suspended matter concentration values with the measured ones indicated a high accuracy of the obtained estimates: the median absolute percentage deviation was 20% (4 km) and 19% (1 km), the median absolute difference was 0.09 mg/L (at both resolutions), the systematic error was −0.2% (4 km) and −0.1% (1 km), and the coefficient of determination was 0.82 (at both resolutions).

Keywords: suspended matter, Black Sea, regional algorithm, satellite optical data, SeaWiFS, MODIS, MERIS, VIIRS, OLCI

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Introduction

Substances in the marine environment are distributed among dissolved, colloidal, and suspended forms. The lower size limit of the suspended fraction corresponds to 0.2–0.45 μm [1, 2], whereas the upper size limit usually does not exceed 1 mm [1]. Marine suspended matter is a mixture of lithogenic and biogenic particles that enter the marine environment through atmospheric deposition, river runoff, coastal abrasion, and the resuspension of bottom sediments or are also produced during biological production [3, 4]. The importance of studying marine suspended matter arises from its key role in biological, geochemical, physicochemical, sedimentary, and optical processes in the marine environment [2, 5, 6].

Classical methods for determining the suspended matter concentration are based on laboratory analysis of seawater samples. The use of such methods does not allow large marine areas to be monitored. In contrast to sampling-based methods, satellite remote sensing systems provide regular information on the state of the surface layer of the sea over vast areas, making them an efficient tool for monitoring the distribution of suspended matter.

Satellite methods for estimating the suspended matter concentration are based on the relationship between the suspended particle concentration and the optical properties of seawater. Suspended particles affect the spectral reflectance of water primarily through changes in the scattering and absorption coefficients. One of the most informative parameters is the particulate backscattering coefficient, which is closely related to the suspended matter concentration and characterises the fraction of light scattered by particles in the backward direction [7–9]. Numerous studies have shown that a stable relationship exists between the particulate backscattering coefficient and the suspended matter concentration, which can be approximated by linear or power functions [9–14]. The coefficient values obtained by approximating the relationship between these parameters are not constant and vary depending on the mineralogical composition of the suspended matter, particle size, and the fraction of organic matter [12]. Therefore, applying the same coefficients to different marine areas can lead to an overestimation or underestimation of the suspended matter concentration [11, 12]. This highlights the importance of obtaining such coefficient values for different marine areas.

Quasi-analytical algorithms are widely used to retrieve the optical properties of seawater from satellite data [9, 15]. One of the most widely used is the algorithm proposed in [16] and known as the Quasi-Analytical Algorithm (QAA). It is based on solving the inverse problem of radiative transfer and allows the spectral absorption and scattering coefficients of seawater to be determined from ocean

[1] Lisitsyn, A.P., 1974. *Sedimentation in the Oceans*. Moscow: Nauka, 438 p. (in Russian).

colour remote sensing data. The algorithm has been repeatedly refined [2], its sixth version is currently available [3].

The optical sensors installed on satellites differ in their sets of spectral bands and spatial resolutions. Consequently, universal coefficients are not applicable when processing these data. This necessitates reassessing the coefficient values for each sensor. For this reason, publications devoted to calculating these coefficient values for a specific sensor family can be found in the available literature [10–13, 17–19]. Meanwhile, researchers from the Plymouth Marine Laboratory (UK) have prepared and made publicly available the Ocean Colour Climate Change Initiative dataset (version 6.0, European Space Agency). In this dataset, measurements obtained from a number of sensors (SeaWiFS, MODIS, MERIS, VIIRS, OLCI) have undergone a correction procedure and have been merged into common spectral bands [4]. Currently, this dataset likely provides the greatest spatial and temporal coverage of the Black Sea region among the publicly available datasets. The dataset is presented in two versions: daily data with a 1-km resolution and daily data on a regular grid with a 4-km resolution. This dataset appears to be the most promising for studying processes (including by means of mathematical modelling) involving suspended matter and covering vast areas of the Black Sea. Despite the high potential of this dataset, regional coefficients for its application to the Black Sea region have not been reported in the available literature.

The purpose of the study is to obtain quantitative estimates of regional coefficients for calculating the values of suspended matter concentrations in the surface layer of the northern and northeastern parts of the Black Sea using the Quasi-Analytical Algorithm (QAA version 6) and daily multi-sensor data (SeaWiFS, MODIS, MERIS, VIIRS and OLCI) with spatial resolutions of 1 and 4 km.

Materials and methods

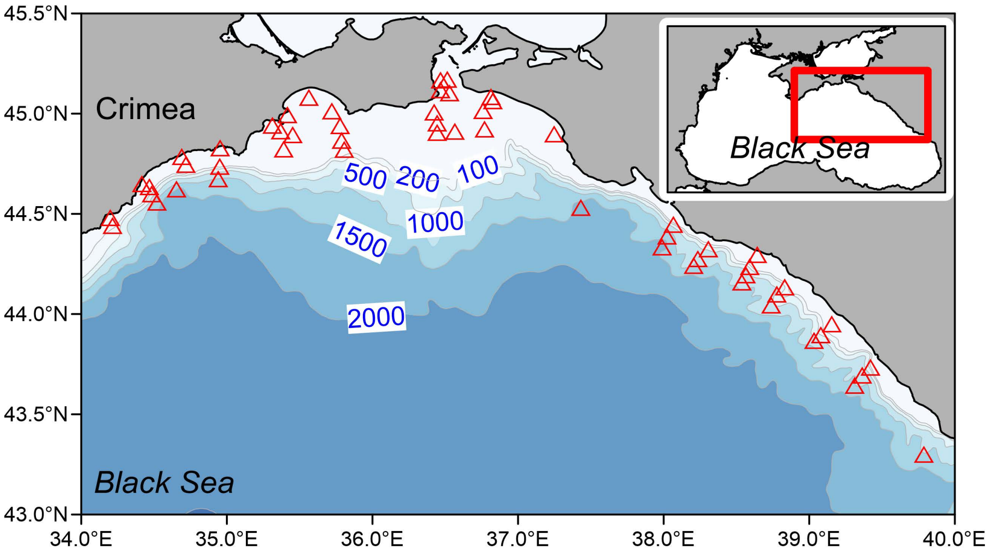
Sampling

In situ data for this study were obtained during the 138th cruise of the R/V *Professor Vodyanitsky* (November 14 – December 9, 2025). Seawater samples were collected from the surface layer of the sea using a plastic container. During the cruise, 56 seawater samples were collected at 56 stations. The layout of the seawater sampling stations is shown in Fig. 1. The distance from each station to the nearest shore varied from 0.5 to 20 km. The water depths at the sampling stations ranged from 7 to 1680 m.

[2] Lee, Z., Lubac, B., Werdell, J. and Arnone, R., 2009. *An Update of the Quasi-Analytical Algorithm (QAA_v5)*. IOCCG, 9 p. (International Ocean Color Group Software Report).

[3] *Steps and Calculations of the Quasi-Analytical Algorithm (QAA_v6)*. [online] Available at: https://ioccg.org/wp-content/uploads/2020/11/qaa_v6_202011.pdf [Accessed: 23 March 2026].

[4] NERC EDS Centre for Environmental Data Analysis, 2023. *ESA Ocean Colour Climate Change Initiative (Ocean_Colour_cci): Global Chlorophyll-a Data Products Gridded on a Sinusoidal Projection at 4km Resolution, Version 6.0.* [online] Available at: https://catalogue.ceda.ac.uk/uuid/474ac06235e54e6cb0ec6eed635e1213 [Accessed: 23 March 2026].



F i g. 1. Location of seawater sampling stations in the Black Sea (the inset shows the area under study indicated by red rectangle)

Determination of the total suspended matter (TSM) concentration

The method used in this study to determine the suspended matter concentration is based on RD 52.24.468-2019 "Mass concentration of suspended solids and dry residue in waters. Methods of measurement by the gravimetric method." The main difference from the above-mentioned procedure was that new and used filters were dried in a drying oven for 24 hours and weighed. The filters were then dried for a further 24 hours and reweighed to confirm the previously determined dry mass. The mass was determined using an Adventurer AR2140 laboratory balance (Ohaus Corp., USA) with a measurement accuracy of 0.1 mg.

Suspended matter was separated from seawater samples directly on board the vessel by vacuum filtration using polyethersulfone membrane filters with a pore size of 0.2 μm and a diameter of 47 mm (FMPES type, manufactured by Vladisart, Russia). The volume of each sample filtered varied from 1.24 to 8.17 L and depended on the suspended matter content of the seawater. The filtrate was collected in 5-litre plastic containers. The mass of the filtered seawater was determined gravimetrically using EK9643K electronic scales (Xiaomi, China) with a measurement accuracy of 1 g. Weighing was carried out on board the vessel during periods of minimal or no rolling. After filtration had been completed, the filter was placed in a plastic Petri dish and frozen at −20 °C until it was dried in a drying oven at the shore-based laboratory. The final suspended matter concentration was calculated by dividing the increase in filter mass by the volume of the filtered sample.

Calculation of the particulate backscattering coefficient

Estimates of the particulate backscattering coefficient (b_{bp}) at a wavelength of 560 nm were obtained using version 6 of the Quasi-Analytical Algorithm (QAA) [3]:

$$\begin{cases} b_{bp}(560) = \frac{u(560)\cdot a(560)}{1-u(560)} - b_{bw}(560), & \text{if} \quad Rrs(670) < 0.0015\ \frac{1}{\text{ave.}} \\ b_{bp}(560) = \left(\frac{u(670)\cdot a(670)}{1-u(670)} - b_{bw}(670)\right)\cdot\left(\frac{670}{560}\right)^{\eta}, & \text{if} \quad Rrs(670) \geq 0.0015\ \frac{1}{\text{ave.}} \end{cases}, \quad (1)$$

where u is a dimensionless parameter equal to the ratio of the backscattering coefficient to the sum of the absorption and backscattering coefficients; a is the absorption coefficient, m^{-1}; b_{bw} is the backscattering coefficient of pure water, m^{-1}; and η is a dimensionless parameter.

The choice of the calculation formula depended on the water type (turbid or clear), which was determined based on the spectral remote sensing reflectance (Rrs) at a wavelength of 670 nm obtained from satellite measurements above the sea surface. Waters were classified as clear if $Rrs < 0.0015\ sr^{-1}$.

Values of b_{bw} at wavelengths of 560 and 665 nm were taken from [20] and were assumed to be $7.5\cdot10^{-4}$ and $3.57\cdot10^{-4}\ m^{-1}$, respectively.

The value of the parameter u was estimated as follows:

$$u(\lambda) = \frac{-g_0 + \sqrt{(g_0) + 4\cdot g_1\cdot r_{rs}(\lambda)}}{2g_1}, \quad (2)$$

where g_0 and g_1 are dimensionless empirical parameters that depend on the solar zenith angle, viewing angle, wind speed, and bio-optical state of natural waters. Although they vary depending on the scattering phase function [9], they were taken to be constants equal to 0.089 and 0.1245, respectively [16]. The parameter r_{rs} is the remote-sensing reflectance immediately below the water surface, sr^{-1}; λ is the wavelength, nm.

The value of r_{rs} was calculated using the following formula

$$r_{rs}(\lambda) = \frac{R_{rs}(\lambda)}{(0.52 + 1.7\cdot R_{rs}(\lambda))}. \quad (3)$$

The value of η was calculated using the formula

$$\eta = 2.0\cdot\left(1 - 1.2\cdot\exp\left(-0.9\cdot\frac{r_{rs}(443)}{r_{rs}(560)}\right)\right). \quad (4)$$

For clear waters, the value of a was calculated using the formula

$$a(560) = a_w(560) + 10^{h_0 + h_1\cdot\chi + h_2\cdot\chi^2}, \quad (5)$$

where a_w is the absorption coefficient of pure water, m^{-1}; h_0, h_1 and h_2 are empirical constants equal to –1.146, –1.366 and –0.469, respectively [3]; χ is a dimensionless parameter depending on the remote-sensing reflectance at wavelengths of 443, 490, 560 and 670 nm.

The values of a_w at wavelengths of 560 and 665 nm were taken from [21] and were assumed to be 0.0619 and 0.4290, respectively.

The values of χ were calculated using the formula

$$\chi = \log\left(\frac{r_{rs}(443) + r_{rs}(490)}{r_{rs}(560) + 5\cdot\frac{r_{rs}(670)}{r_{rs}(490)}\cdot r_{rs}(670)}\right). \quad (6)$$

For turbid waters, the value of a was calculated using the formula

$$a(670) = a_w(670) + 0.39\cdot\left(\frac{R_{rs}(670)}{R_{rs}(443) + R_{rs}(490)}\right)^{1.14}. \quad (7)$$

The remote-sensing reflectance data were obtained from the source [4], they comprised a Level-3 product from version 6. Both data products were used: daily data on a regular grid with a 4-km resolution and daily data with a 1-km resolution.

The algorithms for processing satellite data with 4-km and 1-km resolutions were identical and consisted of the following steps: using the date and coordinates of an individual seawater sampling station, the position of the nearest point in the satellite data array for which data were available for the sampling, preceding and following days was determined. Using these data, the particulate backscattering coefficient values were calculated according to equations (1)–(7). Thus, three particulate backscattering coefficient values were obtained for each station. When calculating regional coefficients, only one of them was used. The specific value was selected as follows. The highest priority was given to the value obtained on the sampling day for the pixel containing the station. The next priority was given to values obtained for the same pixel but on the preceding or following day. Next, values obtained on the sampling day but for a neighbouring pixel were selected when working with data with a 4-km resolution, or the nearest value within a 4-km radius when working with data with a 1-km resolution. The lowest priority was assigned to values obtained on the preceding or following day for a neighbouring pixel when using data with a 4-km resolution, or to the nearest value within a 4-km radius when using data with a 1-km resolution. The proportions of the selected values assigned to the four priority levels, from highest to lowest, were 34.2, 46.3, 2.4 and 17.1% for satellite data with a 4-km resolution and 28.9, 44.8, 2.6 and 23.7% for satellite data with a 1-km resolution.

Statistical characteristics

For the quantitative assessment of the accuracy of the suspended matter concentration values obtained using regional coefficients, the leave-one-out cross-validation (LOOCV) method was applied, and the following statistical characteristics were calculated: median absolute percentage deviation (MAPD), bias, median absolute difference (MAD), and coefficient of determination (R^2). The leave-one-out cross-validation method consists of sequentially excluding one observation from the training set, calculating the coefficients from the remaining $n-1$ points, and calculating the prediction error for the excluded observation. The procedure is repeated for each of the n observations, after which the final metrics (MAPD, MAD, bias, R^2) for assessing the accuracy of the suspended matter concentration estimates obtained using the regional coefficients are calculated from the resulting set of errors. This approach provides an objective assessment of the accuracy of the calculated suspended matter concentration values when the amount of available data is limited.

The median absolute percentage deviation was used to assess the typical relative error, with the resulting estimate being insensitive to outliers in the data series:

$$MAPD = \text{median}\left(\left|\frac{E_i - M_i}{M_i}\right|\right) \cdot 100\,\%,\ i = 1, 2, \ldots N\ , \tag{8}$$

where E_i is the calculated concentration value, mg/L; M_i is the measured concentration value, mg/L.

The bias was used to assess the presence of a systematic error – an overestimation or underestimation of the concentration. Bias was calculated using the following formula:

$$Bias = \text{median}\left(\frac{E_i - M_i}{M_i}\right) \cdot 100\,\%,\ i = 1, 2, \ldots N\ . \tag{9}$$

The median absolute difference, characterising the typical absolute error of the concentration estimate, was calculated using the formula

$$MAD = \text{median}\left(\left|E_i - M_i\right|\right),\ i = 1, 2, \ldots N\ . \tag{10}$$

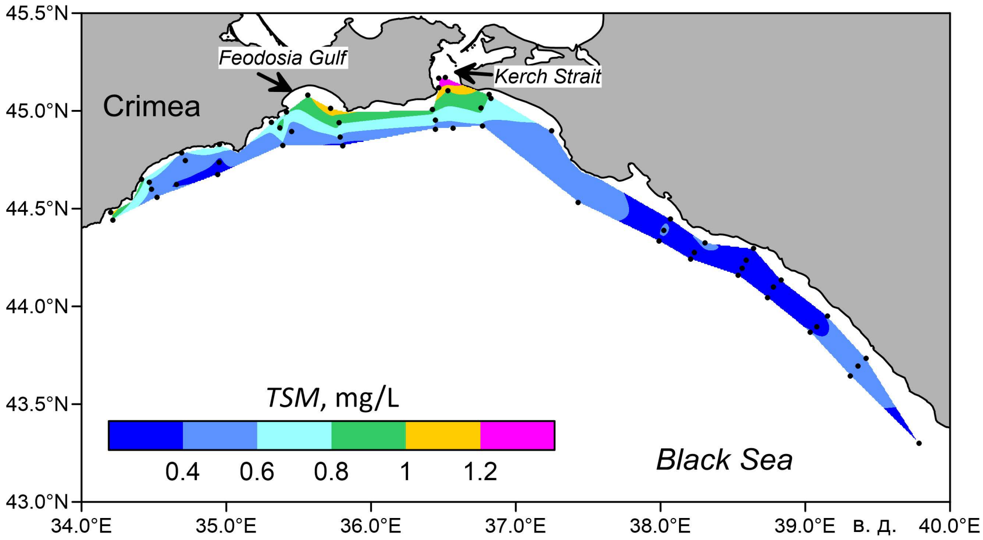
The determination coefficient indicates what proportion of the variance of the observed data is reproduced by the model:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(M_i - E_i\right)^2}{\sum_{i=1}^{n}\left(M_i - \frac{1}{n}\sum_{j=1}^{n} M_j\right)^2}\ . \tag{11}$$

Results and discussion

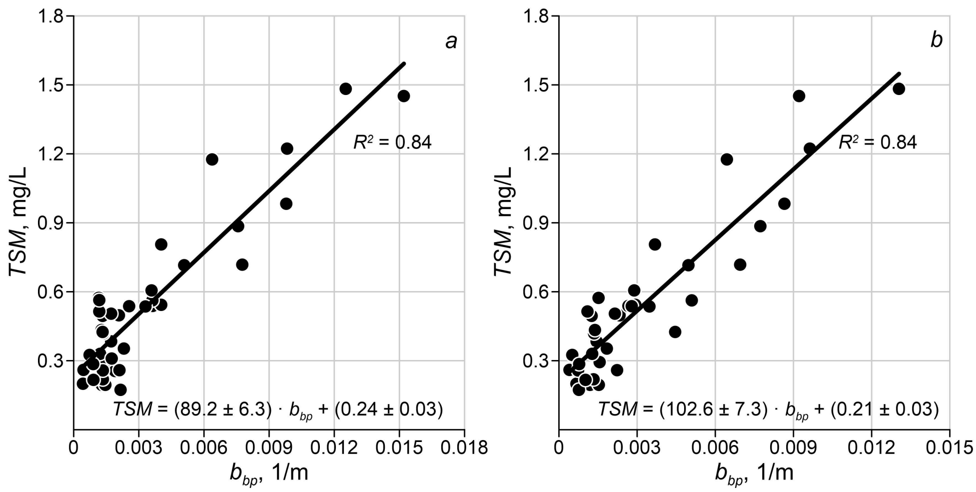
Spatial variability of the suspended matter concentration

The suspended matter concentration in individual samples ranged from 0.17 to 1.48 mg/L. Higher values were observed near the Kerch Strait (1.2–1.48 mg/L) and in Feodosia Gulf (0.9–1.2 mg/L) (Fig. 2). The higher values in Feodosia Gulf are caused by the transport of suspended matter from the Kerch Strait [22, 23]. Lower values were characteristic of the eastern part of the study area (0.17–0.55 mg/L). The observed spatial patterns are consistent with the results of earlier studies [22, 24]. The absolute concentration values also agree with published data: 0.17–0.33 mg/L in December in the deep-water part of the Black Sea [25], 0.3–0.8 mg/L in winter in the deep-water part of the Black Sea [11], and up to 3.8 mg/L in the Kerch Strait area [26].



F i g. 2. Spatial variability of total suspended matter concentration

Regional coefficients for estimating the suspended matter concentration. Using the remote-sensing reflectance data at different wavelengths, the particulate backscattering coefficient values were obtained for each station using equations (1)–(7). Fig. 3 shows a comparison between the suspended matter concentration values and the particulate backscattering coefficient values calculated from the datasets with spatial resolutions of 4 km and 1 km.



F i g. 3. Dependence of suspended matter concentration on the backscattering coefficient for satellite data with a resolution of 4 (*a*) and 1 km (*b*)

The relationship between these parameters was approximated by a linear function. The root-mean-square deviation was minimized during the approximation. The estimated regional coefficients and their uncertainties are shown in Fig. 3.

A comparison of the regional coefficients estimated from the data with 4- and 1-km resolutions shows that they are generally consistent within their uncertainties. It is important to note that the concentration range used to calculate the regional coefficients encompasses the values typical of the open waters of the Black Sea [11, 22, 26].

To assess the accuracy of suspended matter concentration estimates obtained using the calculated regional coefficients, calculations were performed for the same stations as those used to establish these coefficients. The statistical characteristics are given in the Table. According to these characteristics, within the concentration range of 0.17–1.48 mg/L, the median absolute percentage deviation was only 20% (4 km) and 19% (1 km). The low median absolute difference (0.09 mg/L for both resolutions) was most likely due to the fact that most concentration values (75%) were within the range of 0.2–0.6 mg/L. The magnitude of the systematic error was close to zero for both sets of coefficients. Overall, the use of these regional coefficients made it possible to account for 82% of the variability in the *in situ* data.

Statistical characteristics of the quality of obtained estimates of suspended matter concentration, indicating the number of used concentration values (*N*) and their range

Resolution, km	*N*	*TSM*, mg/L	*MAPD*, %	*MAD*, mg/L	*Bias*, %	R^2
4	41	0.17–1.48	20	0.09	−0.2	0.82
1	38	0.17–1.48	19	0.09	−0.1	0.82

Conclusions

The paper presents *in situ* data on the suspended matter concentration in the surface layer of the northern and northeastern parts of the Black Sea during the autumn–winter period of 2025. Water samples were collected 0.5–20 km from the nearest shore, and the water depth at the sampling stations ranged from 7 to 1680 m. The suspended matter concentration in individual samples varied widely, from 0.17 to 1.48 mg/L. Higher values were observed near the Kerch Strait (1.2–1.48 mg/L) and in Feodosia Gulf (0.9–1.2 mg/L). Lower values (0.17–0.55 mg/L) were characteristic of the stations located in the deep-water part of the sea.

Based on the *in situ* data on the suspended matter concentration and the remote-sensing reflectance data with 4- and 1-km resolutions, the regional coefficients for version 6 of the Quasi-Analytical Algorithm (QAA) were determined. This algorithm with the regional coefficients obtained can be used to calculate the suspended matter concentration in the surface layer of the northern and northeastern parts of the Black Sea from merged multi-sensor data (SeaWiFS, MODIS, MERIS, VIIRS and OLCI) with spatial resolutions of 4 and 1 km. The linear regression parameters relating the particulate backscattering coefficient to the suspended matter concentration for the data with a 4-km resolution were 89.2 ± 6.3 (slope) and 0.24 ± 0.03 (intercept), and those for the data with a 1-km resolution were 102.6 ± 7.3 and 0.21 ± 0.03, respectively. The comparison of the calculated suspended matter concentration values with the measured ones within the range of 0.17–1.48 mg/L indicated a high accuracy of the obtained estimates: the median absolute percentage deviation was 20% (4 km) and 19% (1 km), the median absolute difference was 0.09 mg/L (at both resolutions); the systematic error was −0.2% (4 km) and −0.1% (1 km); and the coefficient of determination was 0.82 (at both resolutions).

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