Algorithm for Additional Correction of Remote Sensing Reflectance in the Presence of Absorbing Aerosol: Case Study

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Abstract
Purpose. The main goal of this work is to develop an algorithm for additional correction of Level 2 remote sensing reflectance ocean color satellite data, taking into account the presence of absorbing aerosol over the Black Sea, where a large number of dust transfers from the Sahara are observed annually.
Methods and Results. The research method is based on the comparison of satellite data about remote sensing reflectance from MODIS-Aqua/Terra scanner and *in situ* measurements from AErosol RObotics NETwork Ocean Color (AERONET-OC) stations. The Python mathematical package was used for the data processing: analysis and visualization of satellite images were made in SeaDAS. As a basis for an additional correction algorithm, theoretical calculations were provided to take into account aerosol stratification in the radiative transfer equation, it is shown that for absorbing aerosol the atmospheric correction error is proportional to λ^{-4}. The analytical conclusions were confirmed during the validation of the satellite and the *in situ* measurements using principal component analysis (PCA). The new algorithm is based on the constancy of the color index value, characteristic of the selected region. For the Black Sea, the average value of color index at 412 and 443 nm (CI(412/443)) is approximately equal to 0.80 ± 0.08, a small standard deviation indicates that the sample is slightly variable and considered as the reference value.
Conclusions. The model values of the remote sensing reflectance (Rrs) had a better agreement with the *in situ* values than the satellite Rrs(λ) at Level 2. In the case of the dust aerosol presence, the developed model increases the coefficient of determination between the satellite and the *in situ* values of Rrs(λ) by more than twice at 412 nm, the difference is also noticeable at 443 and 488 nm. The color indices calculated from the model values of Rrs(λ), which are necessary for calculating chlorophyll *a*, are also in better agreement with the AERONET data (an increase in correlation by 20 %).

Keywords: optical characteristics, chlorophyll *a* concentration, ocean color, seawater, absorbing aerosol, dust, MODIS-Aqua, AERONET, Black Sea

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1. Introduction

Information about the biooptical characteristics of sea water is contained in the water-leaving radiance ($L_w(\lambda)$) emerging from the water column [1]. The water-leaving radiance is determined by the optical properties of sea water, which depend on

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the quantitative and qualitative composition of the substance contained in it. The size, shape, and chemical composition of aerosol particles also determine their absorbing and scattering properties, and hence the radiance obtained by a remote sensing instrument. Satellite color scanners, such as MODIS on the Aqua spacecraft (Moderate Resolution Imaging Spectroradiometer), measure the spectral radiance exiting the top of the atmosphere (L_{TOA}), which consists of several components (radiance contribution due to Rayleigh scattering by air molecules, contribution due to aerosols and from surface whitecaps and foam, water-leaving component, as well as glint and residual cloud). The "atmospheric correction" procedure consists in excluding the contributions of all atmospheric and sea surface components from the L_{TOA} value. The difficulty of solving the problem of atmospheric correction is determined by the fact that even in the open part of the World Ocean, which is characterized by a bright blue color, L_w in this region of the spectrum is only about 10–15 % of the total radiance at TOA. In coastal areas, the contribution of L_w to TOA radiance can be even less than 5 % due to the increased absorption by colored dissolved organic matter (CDOM) and suspended matter (phytoplankton cells and detritus) in the water column [2]. As the standard product of the atmospheric correction of satellite data, the remote sensing reflectance Rrs(λ) is used. It can be calculated as the ratio of the normalized water-leaving radiance (L_{WN}) to the solar constant [3].

The main strategy for accounting the atmosphere in remote sensing problems, previously laid down by Gordon and implemented at the first stage in the algorithm [4], was to use the near-IR region to estimate the contribution of atmospheric noise to the signal in the visible region during TOA [5–7]. A more accurate forecast of the influence of the atmosphere, taking into account multiple scattering and using aerosol models, is implemented in the Gordon algorithm [7]. However, in essence, this algorithm remained an extrapolation algorithm. Mathematical estimates show that the extrapolation error of the aerosol scattering value at the wavelength λ is proportional to the value, which is a polynomial of the second degree in the wave number $k = \frac{2\pi}{\lambda}$ in a clean atmosphere [8]. The quadratic dependence of the errors on k is explained by inaccurate estimates of the contribution of the fine fraction of aerosol particles to the radiation scattered by the atmosphere. It should be noted that the results of satellite algorithms are also regularly calibrated using new approaches [9], but despite this, a number of systematic errors of standard algorithms were noted, for example, negative values of remote sensing reflectance in the short-wavelength region at 412 and 443 nm [10, 11].

Basically, the errors are caused by the following reasons: uncertainty in the estimates of the bimodal distribution of aerosol particles; spatial inhomogeneity of the atmosphere (atmospheric fronts, cloud boundaries); absorbing aerosol (dust, smog) and its stratification. The cases of dust loads are characterized by the fact that the average height of absorbing particles is noticeably higher than that of industrial and continental type aerosols [12]. The effect of these factors is exacerbated by the nonlinear dependence of the scattered radiance on the optical thicknesses of the molecular and aerosol components. As a result, a combination of atmospheric correction errors is obtained for the values of the remote sensing reflectance in cases of absorbing aerosol presence over the Black Sea region.

Since absorbing aerosol degrades the quality of standard satellite products, the identification of dust and the determination of its optical properties is a complex problem relevant for the Black Sea. Large errors in the case of using basic algorithms can be avoided only when the real vertical structure of the absorbing aerosol is close to the candidate model, for which the entire aerosol is located in a thin layer of the atmosphere. Thus, it appears that atmospheric correction in the presence of an absorbing aerosol is possible if the general type of the aerosol is known, i.e., the aerosol model can be accurately determined, or if the vertical distribution of the aerosol is similar to that of the candidate aerosol models.

At the moment, there are two algorithms that can take into account the presence of absorbing aerosol, namely the spectral matching algorithm (SMA) and the spectral optimization algorithm (SOA) [13, 14]. Traditional spectral matching algorithms usually adopt the similarity of their absorbance value as the index to evaluate the similarity between two spectra. To use these models in an atmosphere with absorbing aerosols, a set of physical aerosol models is needed that take into account the absorbing and scattering properties of a particular aerosol. Reference tables adapted for each vertical distribution of the aerosol are required. They need to be developed for each specific geographical region to be studied. Morel and Antoine [15] presented another model. This model required a complete solution of the radiative transfer equation and the results were given in the form of interpolation tables. They used MERIS remote sensing reflectance data on two wavelength channels of 510 and 705 nm. Aerosol models were used as initial information for the developed model (e.g. Shettle & Fenn models). In the open part of the World Ocean, including a significant part of the Mediterranean Sea, the set of remote sensing reflectance roughly intersect in the vicinity of 510 nm. If the variability of Rrs(510 nm) compared to the influence of dust aerosol (with the atmospheric correction error in the presence of dust aerosol) is insignificant, then their algorithm can be applied to Case 1 waters. The original definition of Case 1 and Case 2 waters was from Morel and Prieur [16, 17]. In the definition commonly used today, Case 1 waters are those waters whose inherent optical properties (IOPs) are dominated by phytoplankton (e.g., most open ocean waters), whereas Case 2 waters are all other waters (e.g., some coastal and inland waters contain colored dissolved organic matter (CDOM) and inorganic mineral particles in addition to phytoplankton). Unfortunately, at the moment none of the methods described above is widely used for automated atmospheric correction in the presence of dust aerosol.

An alternative method for taking into account the properties of an aerosol is to involve the short-wavelength region (to solve the problem of remote sensing of coastal waters in the visible range (Case 2 water)). As already noted, the contribution of the sea to the signal at TOA is small. Previously, some methods for parameterizing the values of the remote sensing reflectance for the Black Sea waters were proposed. It is known that the shape of the Rrs(λ) spectrum cannot be arbitrary. For the Black Sea, the following methods of parameterization of remote sensing reflectance were proposed: negligible of Rrs(λ) values in the near ultraviolet and constancy of values in the "blue" short-wavelength region [18, 19], estimation of the value of Rrs(412) from the condition of closeness of the corrected spectrum of the remote sensing reflectance to its model spectrum described by two parameters [9]. The main goal of this work is to develop a regional algorithm for additional correction of remote sensing satellite data, taking into account the presence of absorbing aerosol over the Black Sea. The new method can also be used in the absence of dust in order to avoid the need to involve additional information about its presence. To implement the algorithm, an analytical and experimental evaluation of the interpolation function is carried out, taking into account the optical effects caused by the stratification of the absorbing aerosol.

2. Materials

2.1. *In situ* data

One of the most effective instruments of studying the characteristics of atmospheric aerosol, as well as *in situ* measurements of ocean color, is a global network of automated ground stations (platforms) called AERONET (AErosol RObotics NETwork). The advantage of this network is the use of the same type of automatic photometers (Cimel-318) and standardized procedures for calibration and processing of the received data.

For the entire period of operation within the framework of AERONET network, the Black Sea region was represented by 4 regular measuring stations: Sevastopol (44.616°N, 33.517°E), Gloria (44.600°N, 29.360°E), Galata_Platform (43.045°N, 28.193°E) and Eforie (44.075°N, 28.632°E). However, not all stations continue to operate within this network: Sevastopol station ceased to function in 2015. Gloria station is located approximately 12 km off the coast of Romania south of the Danube mouth. In August 2019, this station was replaced by Section-7 (44.45°N, 29.45°E). The water depth in both places reaches about 40 m. Galata_Platform AERONET-OC station, established in 2014, is located approximately 13 km from the coast of Bulgaria opposite the city of Varna. The water depth in this section reaches 35 m.

AERONET network has also been extended to support marine applications. This new network component, called AERONET – Ocean Color (AERONET-OC), provides an additional capability to measure the water-leaving radiance. AERONET-OC plays an important role in ocean color satellite activities through standardized measurements that are a) performed at different locations using a single measurement system and protocol; b) calibrated using an identical reference source and method; and c) processed using the same code.

At the moment, only two Black Sea stations provide information on the ocean color according to the measurements of Section-7_Platform (in the past: Gloria) and Galata_Platform stations. For the western part of the Black Sea, the data on the water-leaving radiance L_w are regularly provided, as well as the normalized water-leaving radiance L_{WN} calculated by the method proposed in [20, 21] to remove the dependence on survey geometry and bidirectional effects in L_w. It is worth noting, since in the future satellite and *in situ* measurements of the water-leaving radiance will be validated and all values of $L_{WN}(\lambda)$ will subsequently be converted to $Rrs(\lambda)$ by dividing by the solar constant $S_o(\lambda)$.

2.2. Satellite data

The source of satellite measurements of $Rrs(\lambda)$ was the results of MODIS-Aqua spectroradiometer measurements. MODIS-Aqua has 36 spectral channels, but only

9 of them were originally related to the ocean color (including the 673-683 nm channel, designed to detect chlorophyll fluorescence excited by solar radiation), the rest were designed to study the atmosphere and the land and determine temperature of surfaces and clouds. MODIS has radiometric sensitivity in 36 spectral channels in the spectral range from 0.4 to 14.4 μm. The size of the scanning swath is 2330 km in the transverse direction (relative to the satellite flight) and 10 km along the flight direction; a global coverage is provided every two days. Based on the measurement data in all MODIS spectral channels, a standard set of 44 values is calculated, including calibrated radiances at the upper boundary of the atmosphere, tied in time and coordinates, as well as various geophysical parameters. In terms of monitoring the state of the ocean, the most interesting are the aerosol optical depth, optical thickness and height of clouds, chlorophyll concentration suspended particles concentration, dispersion index of marine suspension, absorption index of sea water, day and night temperature of the ocean surface.

Remote sensing reflectance (Rrs(λ), sr^{-1}), for MODIS-Aqua data is determined for spectral channels 412, 443, 469, 488, 531, 547, 555, 645, 667, 678 nm. The concentration of chlorophyll *a*, (mg m-3) according to MODIS-Aqua data is calculated using Rrs(λ) values for 2–4 wavelengths from the range of 440–670 nm [22, 23].

3. Methods

In this study, we propose to use an analytical method for accounting for aerosol stratification in the problem of radiation propagation in plane-parallel layers. This is an approximate differential. The equation must reflect the physical meaning of light propagation in an inhomogeneous absorbing medium and, in particular cases, have the simplest solutions to the radiative transfer equation corresponding to known analytical formulas used in the optics of natural media [24–26]. The change in the reflection coefficient of a plane-parallel layer (R), when an infinitely thin layer is added from below at depth z, is equal to the reflectance of an infinitely thin layer multiplied by two transmission functions. The first transmission function $T^d(z)$ describes the decrease in the incident radiation as it passes through the layer. The second function $T^u(z)$ is the attenuation of the radiation scattered by the added layer in the opposite direction. Next, the differential equation is written according to the following equation:

$$\frac{dR}{dz} = T^d(z)T^u(z)\frac{b(z)p(z,\cos\gamma)}{4\mu_1\mu_2},$$
$$\cos\gamma = -\mu_1\mu_2 + \sqrt{1-\mu_1^2}\sqrt{1-\mu_2^2}\cos\varphi, \tag{1}$$

where $b(z)$ is the total scattering (aerosol + Rayleigh) at the depth z; $p(\cos\gamma)$ is the phase function depending on the scattering angle γ; μ_1, μ_2 are the cosine of the zenith angle of incidence onto an infinitely thin layer and the cosine of the zenith angle of the reflection from an infinitely thin layer; φ is the difference of azimuths – azimuth of observation angle and azimuth of the Sun.

We shall assume that τ is the optical thickness of the layer from 0 to z. Then, under the condition that $\tau(z)/\mu_0 < 1$ and $\tau(z)/\mu < 1$, where μ_0, μ are the cosines of the zenith angles of the Sun and the observation angle, we obtain the estimate $\mu_1 \approx \mu_0, \mu \approx \mu_2$. In this case, it is proposed to use analytical expressions for the transmission functions $T^d(z)$

$$T^u(z) = \exp\left[-\frac{1}{\mu}\int_0^z a(x)dx\right], \quad T^d(z) = \exp\left[-\frac{1}{\mu_0}\int_0^z a(x)dx\right],$$
$$a(z) = \frac{d\tau_a(z)}{dz}\left(1 - \Lambda(z)\right), \tag{2}$$

where $a(z)$ is the vertical profile of the aerosol absorption; $\tau_a(z)$ is the aerosol optical thickness (AOT) from the top of the atmosphere up to depth z; $\Lambda(z)$ is the single scattering albedo. The solution of equation (1) for the final layer under condition (2) and the replacement will be expressed through a definite integral:

$$R = \frac{1}{4\mu_0\mu}\int_0^{Z_0} p(\cos\gamma, z)b(z)\exp\left[-\left(\frac{1}{\mu_0} + \frac{1}{\mu}\right)\int_0^z a(x)dx\right]dz\,, \tag{3}$$

where Z_0 is the geometric thickness of the layer. It is noticeable that if $a(z) = 0$, then Gordon's linear approximation is obtained. In current research, we are not interested in solving the indicated approximate equation, but in an analytical estimate of the error in the effects of absorption by aerosol, i.e., difference of two solutions of the equation, at $a(z) = 0$ and and $a(z) \neq 0$:

$$r = R\left(a(z) = 0\right) - R\left(a(z) \neq 0\right).$$

The product $p(\cos\gamma, z)b(z)$ implies the sum of molecular and aerosol scattering. Thus equation (3) is separated on the sum of two integrals. The second term refers only to the optical properties of the aerosol and can formally be considered as part of the aerosol model, the choice of which is based on the signal values in the near-IR range. The first term describes the decrease in the contribution of molecular scattering and, therefore, significantly affects the atmospheric correction error in the short-wavelength part of the visible range. Referring to this, the solution can be written as follows:

$$r = \frac{p_m(\cos\gamma)\tau_m^0(\lambda)}{4\mu_0\mu}a_0(\lambda)\left(\frac{1}{\mu_0} + \frac{1}{\mu}\right)\int_0^1\int_0^z g(x)dxdz,,$$
$$a_0(\lambda) = (1 - \Lambda)\tau_a^0, \tag{4}$$

where $g(z)$ is the power function of aerosol stratification, τ_a^0 is the aerosol optical thickness; τ_m^0 is the total optical thickness of the molecular atmosphere and a_0 is the optical thickness of aerosol absorption. It is worth noting that equation (4) is suitable for any possible distribution in height. In the case of exponential height dependences of aerosol and molecular scattering, the power function of aerosol stratification can be calculated in the following way:

$$g(z) = \frac{1}{\tau_a^0}\frac{d\tau_a(z)}{dz} = \frac{h_m}{h_a}z^{\frac{h_m - h_a}{h_a}}\,;$$

where $h_m \approx 8\ \text{km}, h_a \approx 1.2\ \text{km}$ is the height of the equivalent homogeneous atmosphere for air molecules and aerosol particles. Therefore, the spectral properties of the atmospheric correction error are mainly described with the factor $\tau_m^0(\lambda)$. According to Rayleigh's law, we know that $\tau_m^0 \sim \lambda^{-4}$. Therefore, with an absorbing aerosol, the atmospheric correction error is described by the spectral course of molecular scattering, i.e., proportional to function λ^{-4}.

4. Results and discussions

Based on the above methodology, a simple and efficient algorithm was developed for additional correction of remote sensing reflectance with absorbing aerosol. First of all, the theoretical conclusion should be confirmed experimentally, according to the results of satellite validation (MODIS-Aqua) and *in situ* measurements of the remote sensing reflectance. Additionally, we analyzed 49 cases of dust transport over the Black Sea region (overestimated values of the AOT, underestimated values of the Angstrom parameter (AE) and single scattering albedo (SSA), which is an absorption indicator) and 133 days with a clean homogeneous atmosphere. All selected cases were supported by a visual analysis of satellite imagery (presence of a yellow plume), as well as an analysis of 7-day return trajectories calculated daily by the NASA Goddard Space Flight Center (GSFC) [27]. Some examples of satellite images, where the presence of dust over the Black Sea region is identified, are shown in Fig. 1.

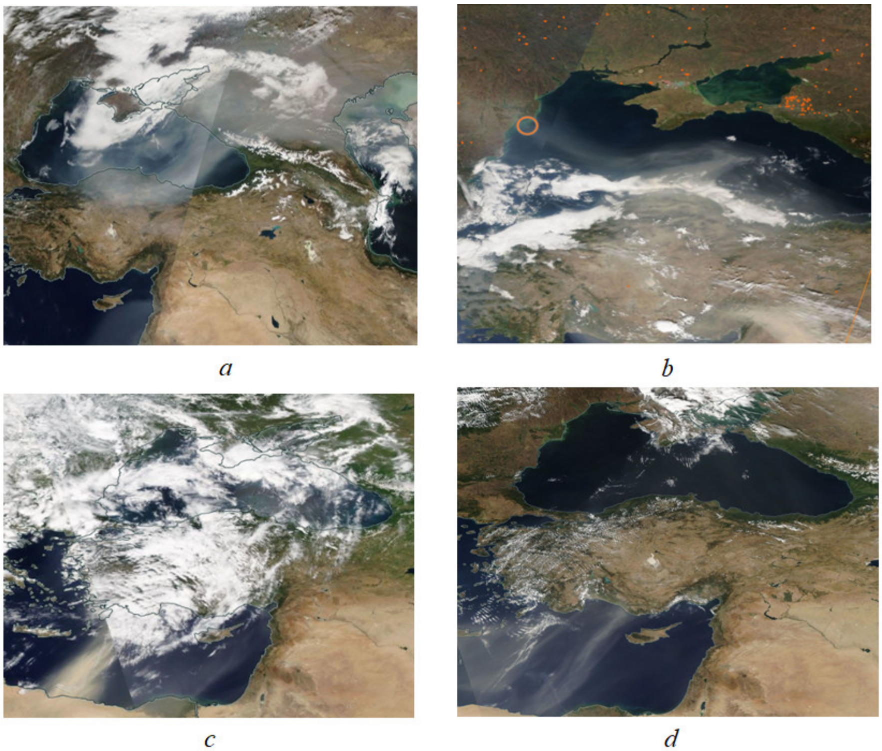
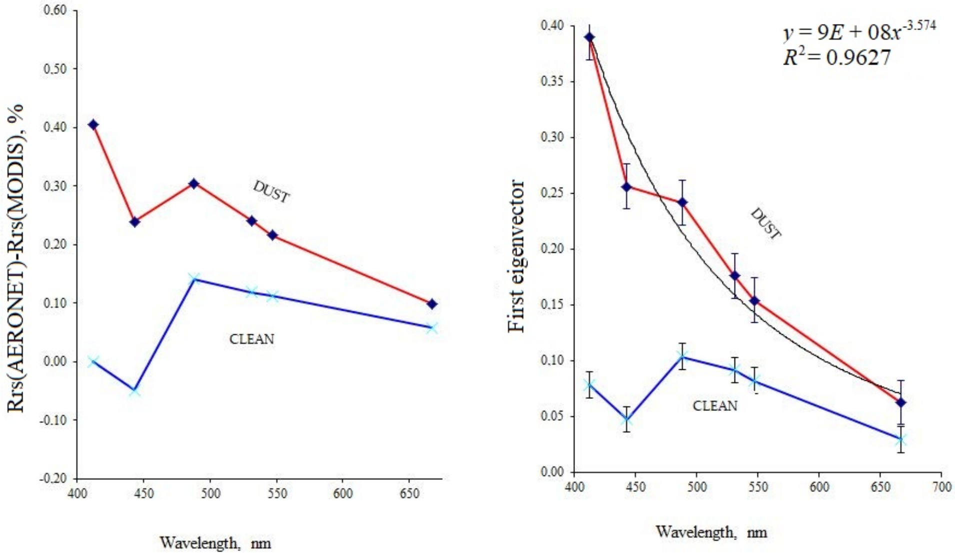

a *b* *c* *d*

Fig. 1. Satellite images from the MODIS-Aqua/Terra platforms during dust transport days with a clear visual presence of a dust plume on 19.10.2017 (*a*), 16.10.2018 (*b*), 14.06.2016 (*c*), 27.09.2020 (*d*)

As a mathematical tool, it is proposed to use the principal component analysis (PCA) to estimate the spectral features of the change in Rrs(λ) in the presence of dust with an estimate of the contribution of the first eigenvector. For a specific task, the difference between the *in situ* values for AERONET stations in the Black Sea and the corresponding satellite values from MODIS-Aqua satellite observations (source: SeaBASS data validation database [28]) (validation error) was taken as a conditional mathematical expectation (Fig. 2).



a *b*

F i g. 2. Validation error for Rrs (between MODIS-Aqua satellite values and AERONET-OC *in situ* measurements) for the Black Sea and the first eigenvector of the covariance matrix

The contribution of the first eigenvector (Fig. 2, *b*) in the presence of dust aerosol was 85 %. When it was approximated, we got the expression $y = 9E + 08\ \lambda^{-3.574}$, where the coefficient of determination was $R^2 = 0.96$. The results of data validation in dusty conditions confirmed the analytical conclusion that, in the presence of absorbing aerosol, the spectral law of atmospheric correction errors is close to λ^{-4} function. This effect is explained by the fact that dust aerosol is determined by the methods of remote sensing using the Gordon and Wang algorithms with an infrared channel, but the arid aerosol has the main effect on the ratio of the aerosol and molecular components. Therefore, for the satellite data of theremote sensing reflectance, an algorithm for additional correction of Level 2 data provided by ocean color for the study region was developed. We assume that the model (restored) values of Rrs(λ) will be calculated by linear regression formula

$$\mathrm{Rrs}_{\mathrm{m}}(\lambda) = \mathrm{Rrs}_{\mathrm{sat}}(\lambda) + k\lambda^{-4}, \qquad (5)$$

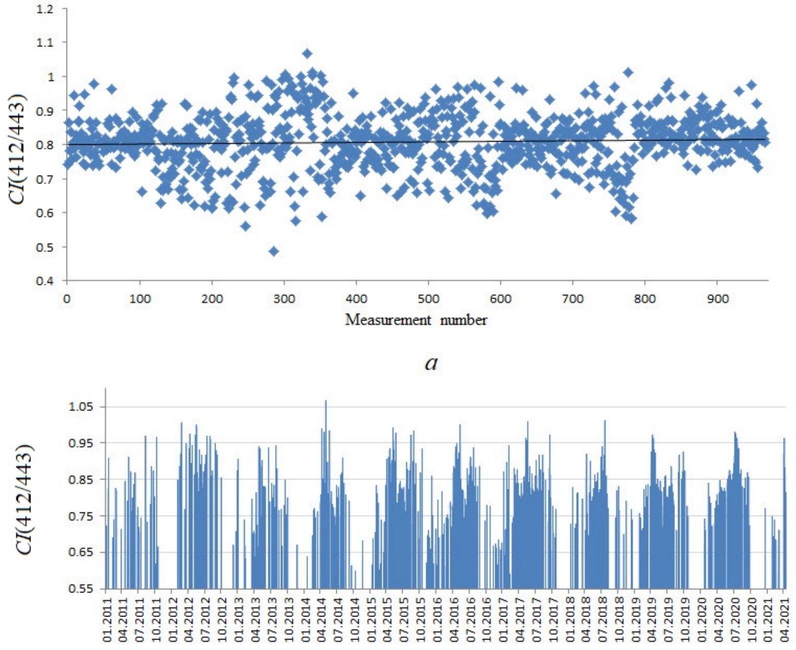
where $\mathrm{Rrs}_{\mathrm{sat}}(\lambda)$ is the value of the remote sensing reflectance obtained by remote sensing methods at wavelength λ; and k is the fitting parameter, which is calculated according to the formula

$$k = \frac{CI(\frac{412}{443})\mathrm{Rrs}_{\mathrm{sat}}(443) - \mathrm{Rrs}_{\mathrm{sat}}(412)}{412^{-4} - CI(\frac{412}{443})443^{-4}}. \tag{6}$$

Since the absorbing aerosol has the greatest influence on errors in the short-wavelength region (negative values at 412 and 443 nm), we propose to calculate k based on the reference value of the color index (CI) for these two channels, calculated from the analysis of the *in situ* measurements (equation (6)).

Thus, assuming k to be constant in the particular case under consideration, using equation (5) we calculate the model values of the remote sensing reflectance at 443, 488, 531, 547, 555 and 667 nm.

To calculate the reference value, an analysis was made of the long-term variability of the spectral radiance according to the measurements from AERONET Gloria and Galata_Platform stations at a quality level of 1.5 (atmospheric correction was carried out). The analyzed sample consisted of 961 spectral values of Rrs(λ) (averaged values per day). It was proposed to analyze the average daily values of Rrs(λ) using the criterion of variability of daily measurements in the short-wavelength region of the spectrum. The ratio of the standard deviation of all measurements per day to the average value of Rrs(λ) for the same day at 412 nm must not exceed 10 %. The selected research area is located in the area of complex waters (Case 2), due to the influence of the river runoff (Dnieper, Dniester, Bug), pronounced summer blooms of coccolithophorids, as well as diatoms and dinophytes in winter period and off-season [29–32] (Fig. 3).



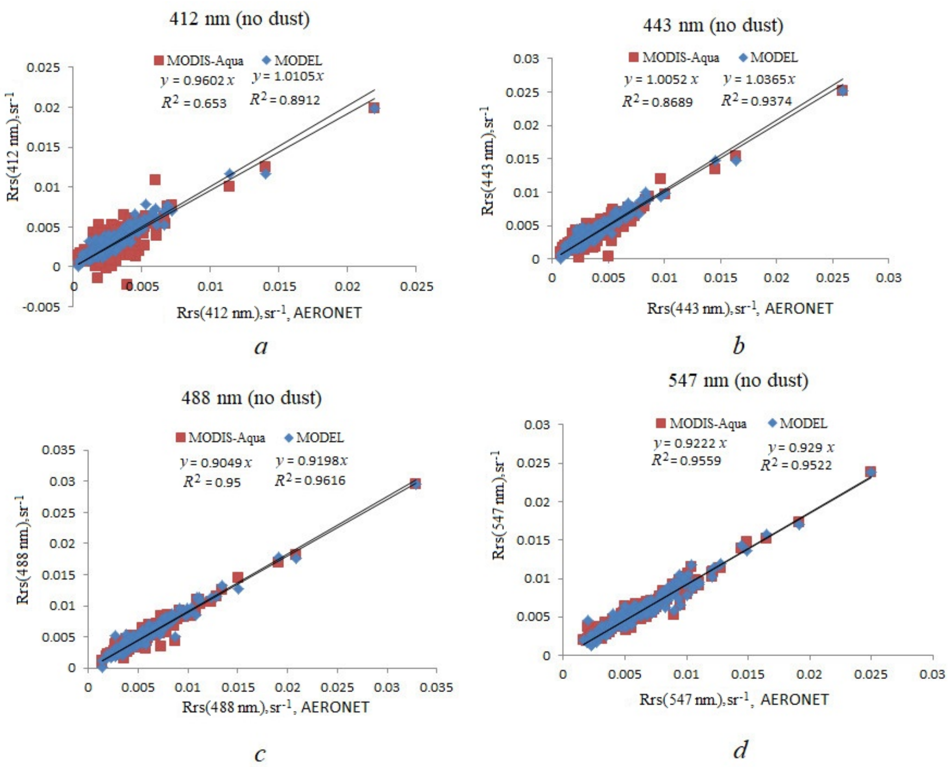
a

b

F i g. 3. Variability of calculated CI(412/443) values based on the *in situ* data from Gloria and Galata_Platform stations from 2011 to 2022 (*a*), seasonality of CI(412/443) (*b*)

The black line on Fig. 3 shows a linear trend. The average value of *CI*(412/443) = 0.80 ± 0.08, a small standard deviation indicates that the sample is slightly variable. Therefore, *CI*(412/443) = 0.80 will be further considered as the reference value of the color index for calculating the k coefficient in equation (6). It is worth noting that the median of the sample is also at 0.80, which indicates an ideal symmetrical distribution. For other color indices using the green region of the spectrum (for example, 443/547 or 488/547), high variability was observed, RMS values were > 20 %. For the Black Sea region, the correction k can be calculated by substituting *CI*(412/443) = 0.8 into equation 6.

The data set under study, consisting of AERONET *in situ* measurements for the Black Sea (SeaBASS) consistent with the three-parameter optical model and the corresponding satellite measurements (from MODIS-Aqua), included 332 values. For each satellite Rrs(λ), the above method was used to calculate the model values of the remote sensing reflectance. Further, a regression analysis of the results was carried out with the calculation of the correlation coefficient with and without a model correction for all cases where there was no dust detected (Fig. 4).


412 nm (no dust)

443 nm (no dust)

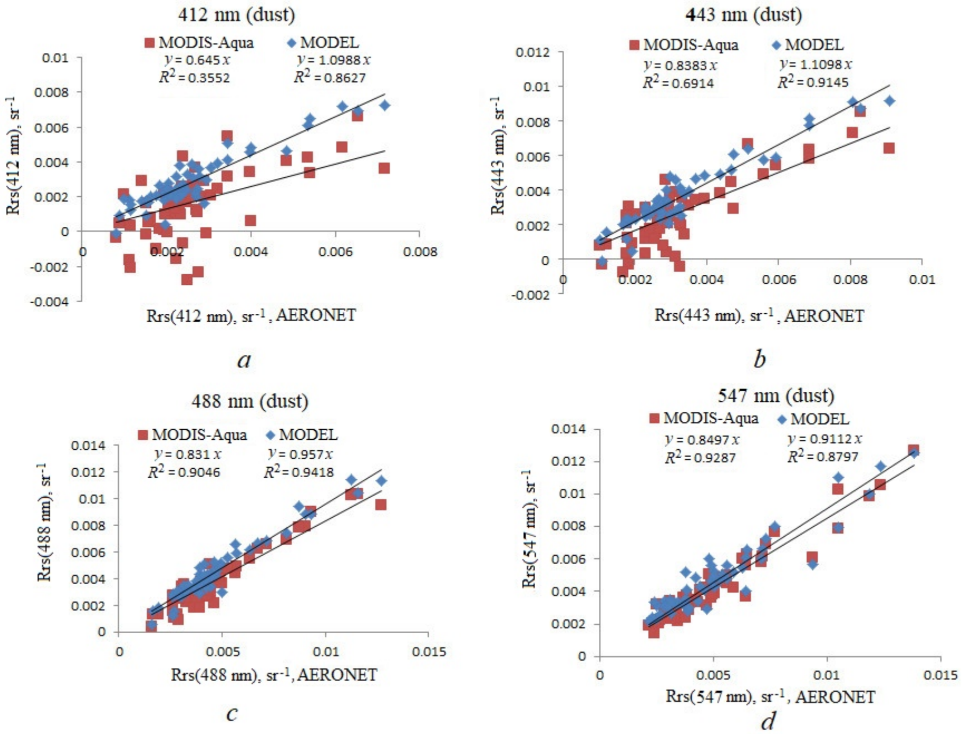
488 nm (no dust)

547 nm (no dust)

a *b* *c* *d*

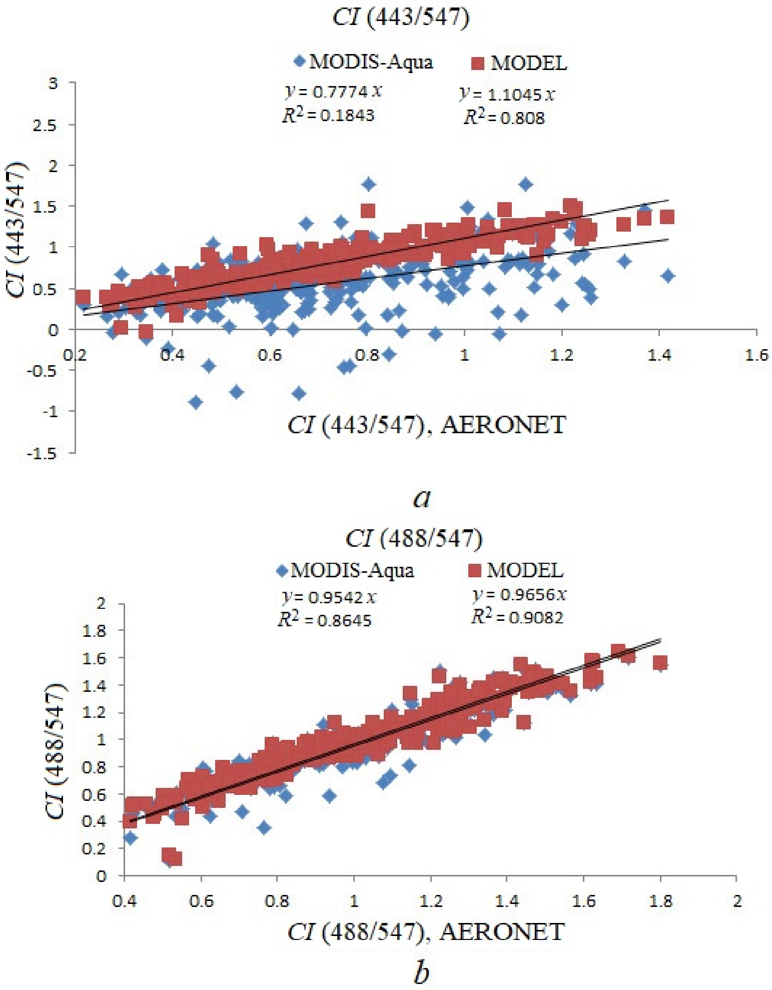
F i g. 4. Linear regression of Rrs(λ) between MODIS-Aqua satellite values and AERONET-OC *in situ* measurements, as well as model values for the northwestern part of the Black Sea at 412, 443, 488, 555 nm for all cases where there is no dust detected

It follows from Fig. 4 that the proposed model correction made it possible to bring satellite values closer to the reliable ones, especially in the short-wavelength region (412, 443 nm). For acceptable models, it is assumed that the determination coefficient must be at least 50 % (in this case, the multiple correlation coefficient exceeds 70 % in absolute value). The models with a determination coefficient above 80 % can be considered quite good (the correlation coefficient exceeds 90 %). The cases of absorbing aerosol presence are of a particular interest. Further, 49 cases of the presence of dust over the Black Sea region will be considered. A similar regression analysis is presented separately for the dust case (Fig. 5).



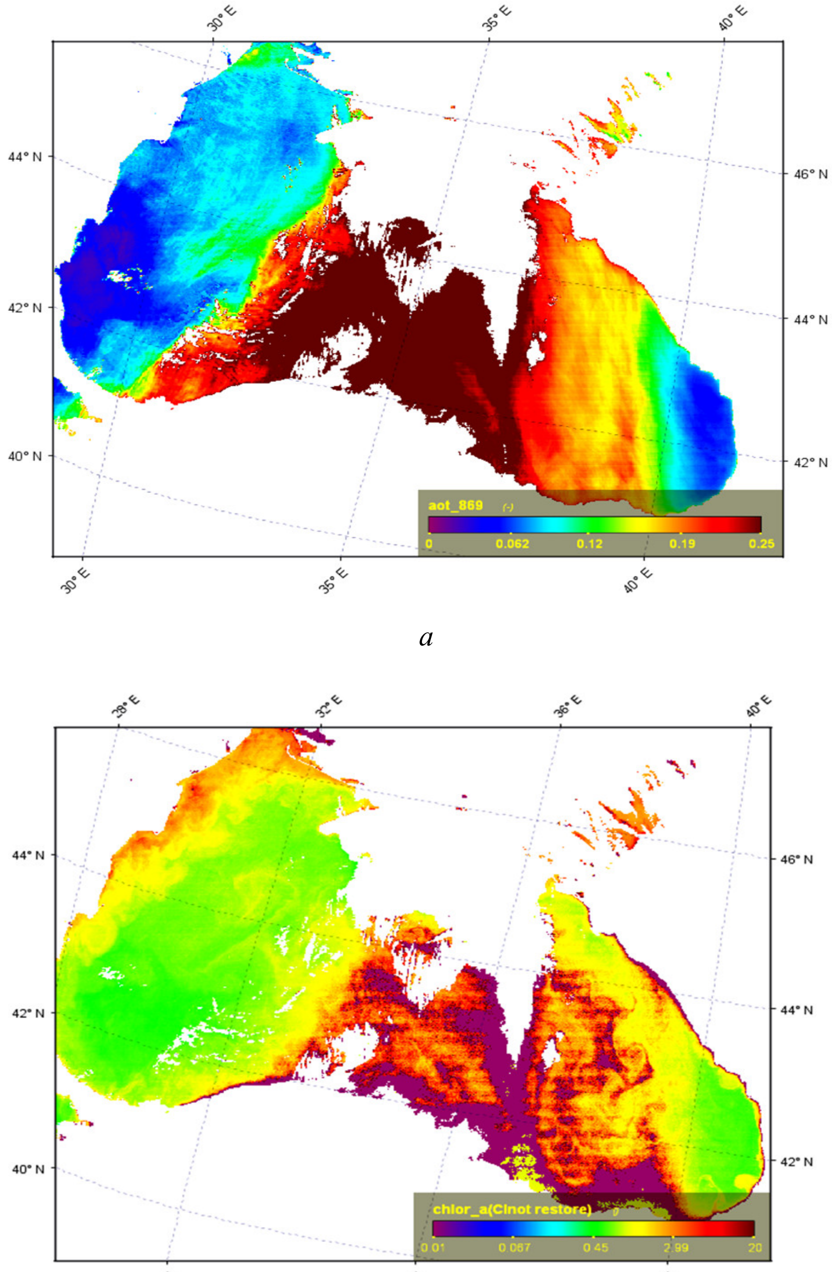
F i g. 5. Linear regression of Rrs(λ) between MODIS-Aqua satellite values and AERONET-OC *in situ* measurements, as well as model values for the northwestern part of the Black Sea at 412, 443, 488, 547 nm for dust loads

It follows from Fig. 5 that in the case of the absorbing aerosol presence, the developed model increases the coefficient of determination by more than twice at 412 nm, the difference is also noticeable at 443 and 488 nm, in the green range of 531–555 nm the changes are insignificant. This algorithm restores satellite values with high reliability during dust transport days over the Black Sea region. The new model correction could have a significant impact on the calculation of color indices used in Ocean Color algorithms to find the concentration of chlorophyll *a*. The most commonly used channel ratio is 443 nm by 547 nm (MODIS-Aqua OC3M) or 488 nm by 547 nm (MODIS-Aqua OC2M). As in the previous cases, the corresponding color indices were calculated from *in situ*, satellite, and model measurements. It was shown that the model values were in better agreement with the *in situ* data, and if without correction the correlation was 50 % (weak), when it was taken into account, it was 70 % (noticeable) (Fig. 6).



F i g. 6. Linear regression of *CI* between MODIS-Aqua satellite values and AERONET-OC *in situ* measurements, as well as model values for the northwestern part of the Black Sea

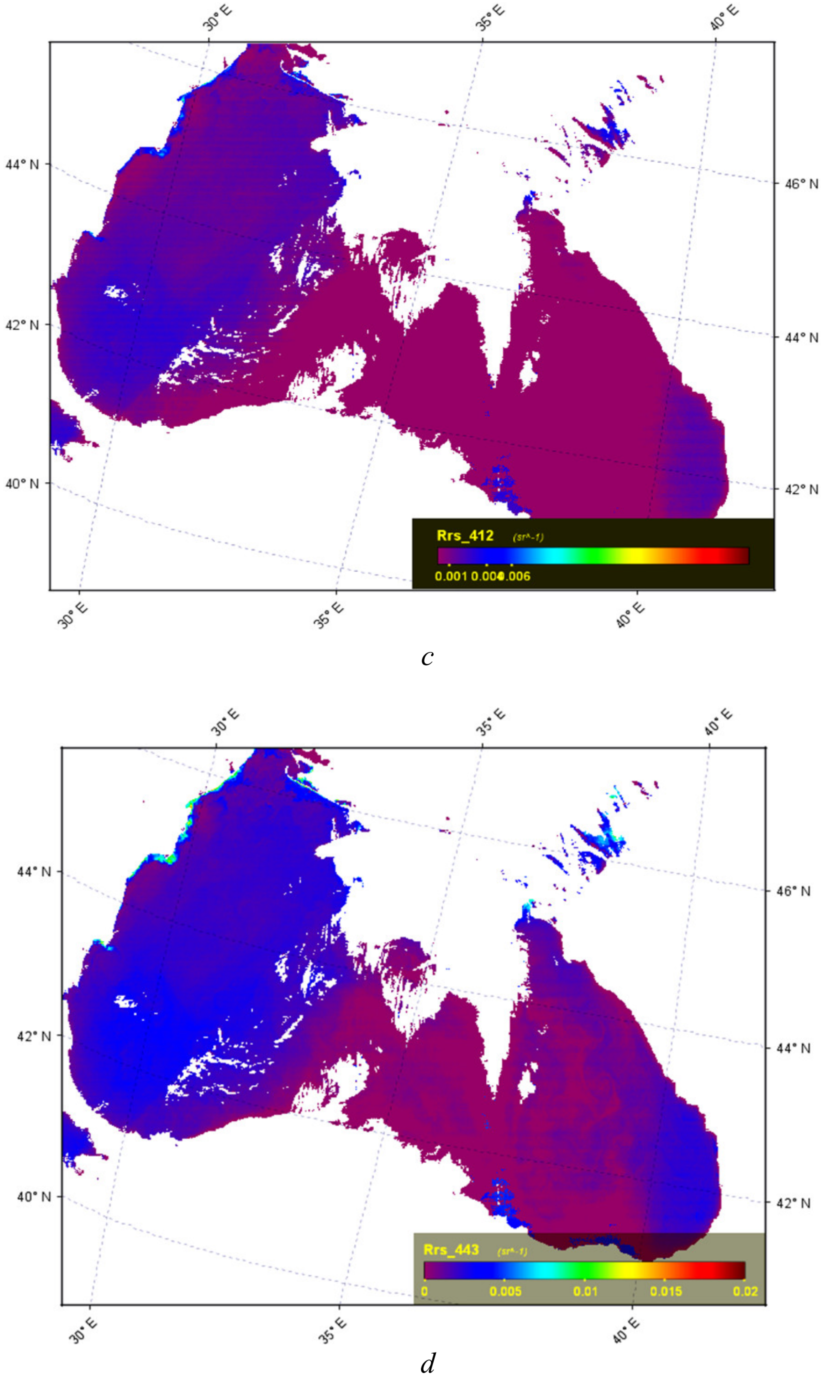
Next, we decided to use an example to consider the principle of restoring color indices. On 27.09.2020, a large-scale dust transport from the Sahara over the Black Sea region was registered (Fig. 1, *d*). According to MODIS-Aqua, the AOT data at 869 nm exceeded 0.25 in the central part of the Black Sea. In the region of 412 and 443 nm, negative values of the remote sensing reflectance were recorded, which in Fig. 7, *c*, *d* are indicated by purple pixels. It should be noted that, perhaps due to the incorrect calculation of the color index in Fig. 7, *b*, some sharp jumps in chlorophyll *a* were found in the central part of the Black Sea.



a

b

F i g. 7. Analysis of the MODIS-Aqua satellite image from 27.09.2020: *a* – AOT distribution, *b* – *CI*(547/443), *c* – Rrs(412 nm), *d* – Rrs(443 nm) built in SeaDAS

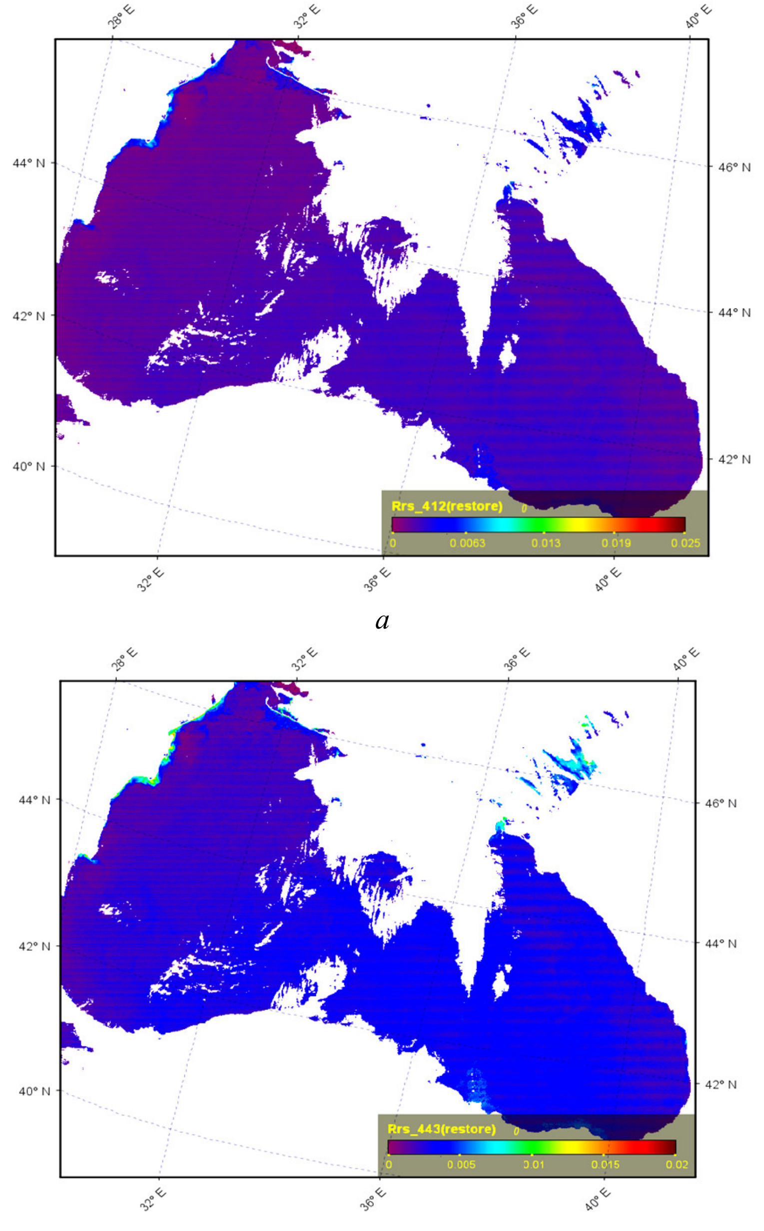


c

d

Continuation of the **Fig. 7.**

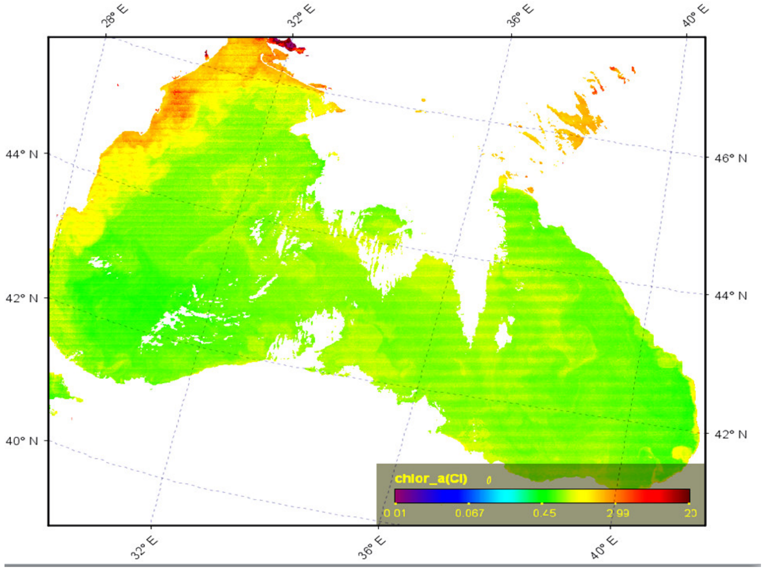
Using the new model correction, we recalculated all Rrs(λ) values for the date under study and got a phenomenal result (Fig. 8). Based on Fig. 8, it can be seen that this correction of the model made it possible to get rid of the negative values in the central part of the Black Sea, where there was no dust, without distorting the data. Also, when recalculating the color indices, which later, when calculating chlorophyll *a*, showed the presence of bloom in the central part, it was found that there was no bloom there, which was confirmed by the long-term expeditionary observations in the Black Sea in September. We carried out a similar analysis for other cases of dust presence over the Black Sea region and found an improvement in the quality of MODIS-Aqua information.



a

b

F i g. 8. MODIS-Aqua satellite image data from 27.09.2020, taking into account correction of the model: *a* – Rrs(412 nm) restored; *b* – Rrs(443 nm) restored; *c* – *CI*(547/443) restored (built in SeaDAS)



c

Continuation of the **F i g. 8.**

Similarly, we considered the new model for cases with a clean atmosphere in order to avoid distortion of obviously good values and found that this model correction does not distort the correct results. For example, if we consider the case of the MODIS-Aqua satellite image from 12.07.2020, we will notice that the AOT values at 869 nm are low (the average value was 0.062), which may indicate a clean atmosphere. We also detected a small bloom of coccolithophorids in the central part of the Black Sea. When we analyzed the spectral remote sensing reflectances mall deviations in the values were noted. After correcting the new model, the data did not change, were are no obvious distortions. After considering many cases, we came to the conclusion that this correction of the model can be used even in the absence of absorbing aerosol, even in cases of phytoplankton blooms.

5. Conclusion

To develop the algorithm, it was necessary to provide analytical estimates to take into account aerosol stratification in the radiative transfer equation, and to prove that dust aerosol affects the value of the atmospheric correction error. In this paper, we propose an approach to describe the effect of stratification of an absorbing aerosol. The factors affecting the difference between the reflection coefficients of the atmosphere with non-absorbing and absorbing aerosol are identified. The spectral dependence of molecular scattering, the spectral properties of its absorption by aerosol, the stratification, and the geometric factor are included in the composition as factors.

First of all, we are interested in the form of the spectral function in order to use it as an interpolation function for atmospheric corrections errors. In this study, it is shown that, with absorbing aerosol, the atmospheric correction error is described by the spectral course of molecular scattering, i.e. proportional to λ^{-4}. This is due to the absorption of the molecular component by the aerosol particles.

The analytical conclusions were confirmed during the validation of satellite and *in situ* measurements. To analyze the characteristic trends in the absolute error of satellite and *in situ* Rrs(λ), the PCA was used for the selected dates with an estimate of the contribution of the first eigenvector of the covariance matrix. As a result, it was found that the largest difference between the satellite and the *in situ* measurements is present in the case of dust aerosol, since the average difference in the remote sensing reflectance is maximum. In the presence of absorbing aerosol, an explicit systematics is observed, namely, when approximating the first eigenvector for MODIS, we obtained $y = 9E + 08\lambda^{-3.574}$. The spectral course of the first vector in cases of dust shows a tendency to increase in the short-wavelength region with an intermediate local maximum of about 500 nm and a sharp decrease in values in the long-wavelength region of the spectrum. This effect is explained by the fact that dust aerosol is determined by remote sensing methods using the Gordon and Wang algorithms with the help of the infrared channel. However, the arid aerosol has the main influence on the ratio of aerosol and molecular components.

The main goal of this work was to develop an additional algorithm for correcting satellite data for the Black Sea (northwestern part). The proposed model correction is based on the patterns of Rrs(λ) variability in this region; it was shown that the color index $CI(412/443)$ is slightly variable for the northwestern part of the Black Sea and varies within 0.80 ± 0.08. The model values of the remote sensing reflectance had a better agreement with the *in situ* values than the satellite Rrs(λ) at Level 2. In the case of the absorbing aerosol presence, the developed model increases the coefficient of determination R^2 between the satellite and the *in situ* values of Rrs(λ) by more than twice at 412 nm, the difference is also noticeable at 443 and 488 nm, in the green range of 531–555 nm the changes are insignificant. The color indices calculated from the model values of Rrs(λ), which are necessary for calculating chlorophyll *a*, are also in better agreement with the AERONET data (an increase in correlation by 20 %).

We assume that the developed technique can be further used for other water areas affected by absorbing aerosols (dusty regions). These can be other AERONET platforms with the ocean color extension, or other research areas where sufficient spatio-temporal coverage is provided by in-situ measurements to identify patterns in the change of color indices. The big advantages of the developed algorithm are its implementation simplicity, possibility to be used even in the absence of dust without any data distortion, and a small set of input parameters.

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