Article

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

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Abstract: In the presence of absorbing aerosol in the atmosphere a number of systematic errors of standard Ocean Color algorithms were noted, for example, negative values of remote sensing reflectance in the short-wavelength region at 412 nm and 443 nm. The main goal of this work is to develop an algorithm for additional correction of remote sensing reflectance level 2 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. 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. This algorithm is based on the constancy of the color index value, characteristic of the selected region. For the Black Sea 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 new restored Rrs(λ).

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

1. Introduction

Information about the biooptical characteristics of sea water is contained in the water-leaving radiance that emerged from the water column Lw(λ) [1]. The water-leaving radiance is determined by the optical properties of sea water, which depend on 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 Aqua (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, the contribution due to scattering by aerosols and contribution from surface whitecaps and foam, the water-leaving component). 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 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 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 is can be calculated as the ratio of the normalized water-leaving radiance (L_WN) to the solar constant [3].

At the initial stage of satellite monitoring of the ocean color within the framework of the CSZS (Costal Zone Color Scaner) mission, it was not expected that, in order to achieve

the required accuracy, taking into account the variability of the optical characteristics of aerosol is a major scientific problem [4]. The main strategy, laid down earlier by Gordon, and implemented at the first stage in the algorithm [6], was to use the near-IR region to estimate the contribution of atmospheric noise to the signal in the visible region at 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 Gordog-Wang algorithm [8]. 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 $k = \dfrac{2\pi}{\lambda}$ in a clean atmosphere [9]. 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 [10], 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 nm and 443 nm [11-12].

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 [13]. 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 SOA spectral optimization algorithm [14-15]. 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 are required adapted for each vertical distribution of the aerosol. They need to be developed for each specific geographical region to be studied. Morel and Antoine [16] presented other 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 (for example SF79 models). In the open part of the World Ocean, including a significant part of the Mediterranean Sea, the set of remote sensing reflectance approximately intersect in the vicinity of 510 nm. If the variability of Rrs(510) 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 increase in Rrs(510) can be influenced by household waste in the form of plastic, which is currently a major problem of pollution of the world's oceans [17]. Un-

fortunately, 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 smallness 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 and Methods

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 the global network of observation ground automated stations (platforms) AERONET (Aerosol ROboties NETwork). The advantage of this network is the use of the same type of automatic photometers and standardized procedures for calibration and processing of the received data (Cimel-318 (CE-318)). For the entire period of operation within the framework of the AERONET network, the Black Sea region was represented by 4 regularly measuring stations: Sevastopol (44.616N, 33.517E), Gloria (44.600N, 29.360E), Galata_Platform (43.045N, 28.193E) and Eforie (44.075N, 28.632 e). However, now not all stations continued to operate within this network: the Sevastopol station ceased to function in 2015. The Gloria site is located approximately 12 nautical miles off the coast of Romania south of the mouth of the Danube. In August 2019, this site was replaced by Section-7 (29.45°E, 44.45°N). The water depth in both places is about 40 m. The Galata_Platform AERONET-OC site (28.19°E, 43.05°N), established in 2014, is located approximately 13 nautical miles from the coast of Bulgaria in front of the city of Varna. The water depth in this section is 35 m. The AERONET network has also been extended to support marine applications. The AERONET network, developed for atmospheric research at various scales, has been expanded to support marine applications. This new network component, called AERO-NET - 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 past: Gloria) and Galata_Platform stations. For the western part of the Black Sea, 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 by Zibordi et al. [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(λ) by dividing by the solar constant $S_o(\lambda)$.

AERONET OC values will be taken as reference values in the validation analysis of satellite and in situ measurements. All in situ measurements were additionally checked for compliance with the model remote sensing reflectance, which are linearly dependent on the ratio of light backscattering by sea water to absorption. The model value of non-dimensional reflectance which can be computed as $Rrs(\lambda) \cdot \pi$ should be written as [22]:

$$\rho(\lambda) = s \cdot b_b(\lambda)/a(\lambda)$$

where s is the coefficient of proportionality depending on the phase function, more precisely on the geometry and observation conditions. We used the value s = 0.15. Backscattering, in turn, can be described by formula as [23]:

$$b_b(\lambda) = b_{bw}(\lambda) + b_{bp}(\lambda_0)\frac{\lambda_0}{\lambda}$$

Absorption was written as a sum of three terms with two unknowns [24]:

$$a(\lambda) = a_w(\lambda) + C_{chl}a_{ph}^*(\lambda) + C_{ddm}e^{-0.015(\lambda-\lambda_0)}$$

where is the C_{chl} concentration of chlorophyll, C_{ddm} is the concentration of organic matter, detritus + yellow matter, a_w is the absorption rate of pure water, a_{ph} is the specific absorption index of phytoplankton according to the model described in [25] at a given concentration of chlorophyll C_{chl}=0.75 mg/m3, corresponding to the data of the work [26]. Next, a search was made for the minimum residual of the model and in situ $Rrs(\lambda)$ values with its allowable limit values, the value of the residual should not exceed . 87% of all values provided by AERONET were consistent with this model. The remaining emissions may be associated with the non-accounting for polarization during measurements, the error in accounting for the reflected component (heterogeneity of the sky, waves, polarization).

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 are designed to study the atmosphere and land and determine temperature surfaces and clouds. MODIS has radiometric sensitivity in 36 spectral channels in the spectral range from 0.4 to 14.4 μm. Channels 1-2 have a spatial resolution of 250 m, channels 3-7 - 500 m, the rest (8-36) - 1000 m. 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; global coverage is provided every two days. In-flight calibration is provided by four calibration devices on board, including a spectroradiometric calibration device and a black body. After data recalculation (reprocessing) performed by NASA specialists in 2009-2011. (https://oceancolor.gsfc.nasa.gov), the number of channels for calculating biooptical characteristics was increased to 12 by using data in channels 1, 3-4, recalculated to a pixel size of 1 km. 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, and various geophysical parameters. For monitoring the state of the ocean, the most interesting are the aerosol optical depth, the optical thickness and height of clouds, the concentration of chlorophyll, the concentration of suspended particles and the dispersion index of marine suspension, the absorption index of sea water, as well as day and night temperature of the ocean surface.

Remote sensing reflectance ($Rrs(\lambda)$) (sr-1), for MODIS 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 data is calculated using $Rrs(\lambda)$ values for 2-4 wavelengths from the range of 440-670 nm [27-28].

3. Results

3.1. An analytical method for accounting for aerosol stratification in the problem of radiation propagation in plane-parallel layers.

To describe the effect of absorbing aerosol on radiation transfer, it is proposed to use the principle of interaction of plane-parallel layers, which works with the transmittance (T) and reflection coefficients of a plane-parallel layer (R) [29-31]. The reflectance as long as transmittance is expressed through upward and downward radiance and can be calculated as:

$$R,T = \frac{\pi \cdot L}{\mu_0 F_0}$$

Where L is upward or downward radiance at the boundary of the layer, μ_0 − cosine of the Sun's zenith angle. $F_0(\lambda)$ – irradiance of perpendicular surface. For generality, the transmission function includes direct light attenuated according to Bouguer's law, i.e.

$$T = \frac{\pi \cdot L_{sc}}{\mu_0 F_0} + \frac{\pi}{\mu_0} \exp[-\tau/\mu_0] \cdot \delta(\mu_0 - \mu) \cdot \delta(\varphi_0 - \varphi)$$

where L_{sc} is scattered radiance; τ – optical thickness of the layer; $\delta(x_0 - x)$ – Dirac delta-function; μ – cosine of observation zenith angle; φ_0, φ – azimuth angles. According to the theory both R and T is considered as operator X working with arbitrary radiance field $L_0(\mu_0, \varphi_0)$:

$$\hat{X} \cdot L_0 = \frac{1}{\pi} \int_0^{2 \cdot \pi} \int_0^1 X(\mu, \varphi, \mu_0, \varphi_0) \cdot L_0(\mu_0, \varphi_0) \mu_0 d\mu_0 d\varphi_0$$

For inhomogeneous layers, one should distinguish between reflection and transmission of the layer when light falls from above and below. For an optical system consisting of two layers, the corresponding operators are determined from the solution of the system of linear equations. In a case when the second layer is optically thin we do not need to take into account the re-reflection between layers. Then the total reflectance will be following:

$$\hat{R} = \hat{R}_1 + \hat{T}_1^u \cdot \hat{R}_2 \cdot \hat{T}_1^d \tag{1}$$

where upper index means number of layer, while lower does direction of propagation for the radiance. For an approximate estimate, let's move from (1) to the scalar form: For an approximate estimate, let's move from (1) to the scalar form:

$$R = R_1 + T^u T^d R_2 \tag{2}$$

In the present case, the layer is added from below and the vertical axis is directed downwards. Since the reverse direction of the vertical axis is accepted in the optics of the atmosphere, then (instead of the dependences of optical characteristics on height) we will assume that the scattering and absorption indices depend on the ratio of atmospheric pressure at a given height $P(h)$ to atmospheric pressure at sea surface level P_0. Thus, the dimensionless depth value can be calculated as $z = P(h)/P_0, z \in [0, 1]$. Consequently, $d\tau_m/dz = const = \tau_m^0$, where τ_m – is the optical thickness of the upper layer of the molecular atmosphere at a specific height (*h*), τ_m^0 – is the total optical thickness of the molecular atmosphere. In turn, the optical characteristics of an aerosol depend on its stratification. Since the second layer is thin, there is an analytical expression for the reflectance:

$$R_2 = \frac{p(\cos \gamma) b(z) dz}{4 \mu \, \mu_0} \tag{3}$$

Where $b(z)$ is the total scattering (aerosol+Rayleigh) at the depth z, $p(\cos\gamma)$ is the phase function depending on scattering angle γ , $\cos\gamma = \sqrt{1-\mu^2}\sqrt{1-\mu_0^2}\cos(\varphi-\varphi_0)-\mu\cdot\mu_0$.

Substituting (3) into (2) we get:

$$\frac{dR}{dz} = T^u(z)\cdot T^d(z)\cdot\frac{p(\cos\gamma)\cdot b(z)}{4\mu_0\mu} \tag{4}$$

We consider this mechanism from the point of view that the scattered radiance passes through an absorbing aerosol. That is why we should estimate T functions. In a single-order approximation T functions account attenuation due to scattering and absorption. Indeed, the attenuation due to scattering is compensated by a multiple scattering, especially for anisotropic phase function, i.e. $p(\cos\gamma)<1$. If T1 and T2 are considered equal to 1, then this will be Gordon's linear approximation. In this case, we propose to take into account the absorption in the transmission functions by introducing the vertical profile of the aerosol absorption as $a(z)=\frac{d\tau_a(z)}{dz}\cdot(1-\Lambda(z))$, where $\tau_a(z)$ is aerosol optical depth from the top of atmosphere up to depth z, $\Lambda(z)$ – single scattering albedo. In the case of exponential height dependences of aerosol and molecular scattering, the aerosol stratification function has the form of a power function $g(z)=\frac{1}{\tau_a^0}\frac{d\tau_a(z)}{dz}=\frac{h_m}{h_a}z^{\frac{h_m-h_a}{h_a}}$, where τ_a^0 – AOT and $h_m\approx 8\,km, h_a\approx 1.2\,km$ – the height of the equivalent homogeneous atmosphere for air molecules and aerosol particles. We propose to take into account the absorption in the transmission functions by introducing a(x) - the variability of the absorption with respect to height:

$$T^u(z)=\exp\left[-\frac{1}{\mu}\int_0^z a(x)dx\right], T^d(z)=\exp\left[-\frac{1}{\mu_0}\int_0^z a(x)dx\right] \tag{5}$$

Formula (4) can be represented as a sum with the substitution of the expression for T.

$$\frac{dR}{dz}=\frac{p_m(\cos\gamma)\cdot b_m(z)}{4\mu_0\mu}\exp\left[-\left(\frac{1}{\mu_0}+\frac{1}{\mu}\right)\cdot\int_0^z a(x)dx\right]+\frac{p_a(\cos\gamma)\cdot b_a(z)}{4\mu_0\mu}\exp\left[-\left(\frac{1}{\mu_0}+\frac{1}{\mu}\right)\cdot\int_0^z a(x)dx\right]$$

where the subscripts *m* and *a*– refer to molecular and aerosol scattering, respectively.

In the present work, 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 at $a(z)\neq 0$.

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

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 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, formula (4) can be written as:

$$\frac{dr}{dz}=\frac{p_m(\cos\gamma)\cdot\tau_m^0}{4\mu_0\mu}\left(1-\exp\left[-\left(\frac{1}{\mu_0}+\frac{1}{\mu}\right)\cdot a_0\int_0^z g(x)dx\right]\right) \tag{6}$$

Where $a_0=(1-\Lambda)\tau_a^0$ – optical thickness of aerosol absorption.

It should be noted that the value of the integral $\int_0^z g(x)dx<1$ due to stratification and $(1-\Lambda)<<1$. The value of AOT multiplied by the geometric factor is limited by the possibility of observing the sea color, then the exponent indicator is small. Then the

expression for the atmospheric correction error due to the stratification of the absorbing aerosol has the form

$$r = \frac{p_m(\cos\gamma) \cdot \tau_m^0(\lambda)}{4\mu_0\mu} a_0 \cdot \left(\frac{1}{\mu_0} + \frac{1}{\mu}\right) \int_0^1 \int_0^z g(x)dx \cdot dz \qquad (7)$$

where the factor a_0 takes into account the absorbing properties of the aerosol, observation geometry is taken into account in $\frac{p_m(\cos\gamma)}{\mu_0\mu}\left(\frac{1}{\mu_0} + \frac{1}{\mu}\right)$, while the double integral does not depend on the wavelength and takes into account the stratification of the absorbing aerosol with respect to air molecules. Therefore, the spectral properties of the atmospheric correction error are mainly described with a factor $\tau_m^0(\lambda)$. According to Rayleigh's law, we know that $\tau_m^0 \approx \lambda^{-4}$. Therefore, with an absorbing aerosol, the atmospheric correction error is described by the spectral course of molecular scattering, i.e. close to λ^{-4}.

3.2. Algorithm for additional correction of remote sensing reflectance with absorbing aerosol, experimental confirmation.

The theoretical conclusion should be confirmed experimentally, according to the results of validation of satellite (Modis Aqua) and in situ measurements of theremote sensing reflectance. Additionally, we analyzed 49 cases of dust transport over the Black Sea region (overestimated values of the aerosol optical depth (AOD), underestimated values of the Angstrom parameter (AE) and SSA(single scattering albedo) (absorption indicator)) and 133 days with a clean homogeneous atmosphere. All selected cases were supported by visual analysis of satellite imagery (presence of a yellow plume), as well as analysis of 7-day return trajectories calculated daily by the GODDART center [32]. Some examples of satellite images where the presence of dust over the Black Sea region is identified are shown in Figure 1.

(a)   (b)

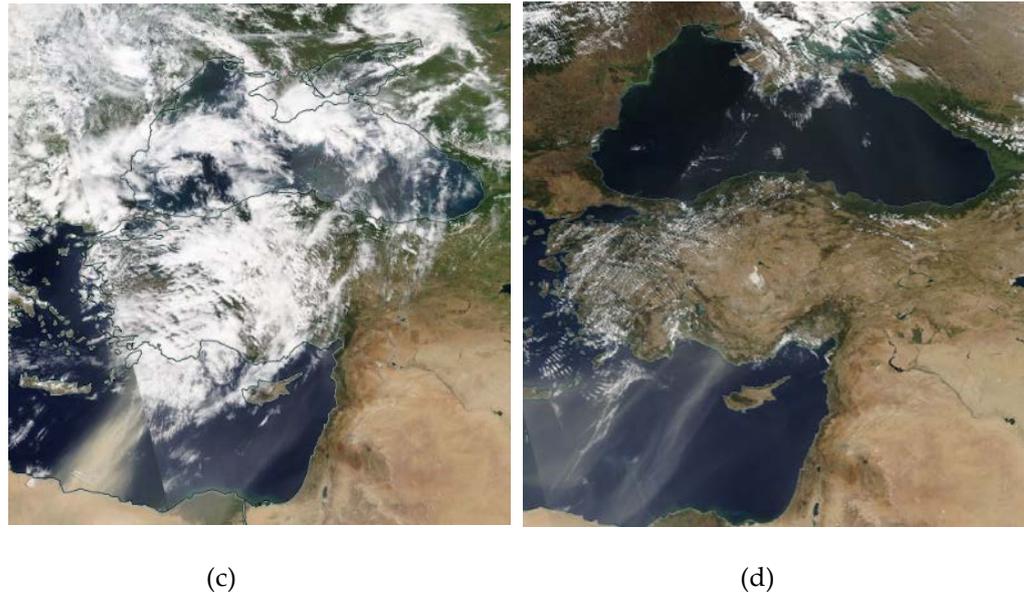(c)   (d)
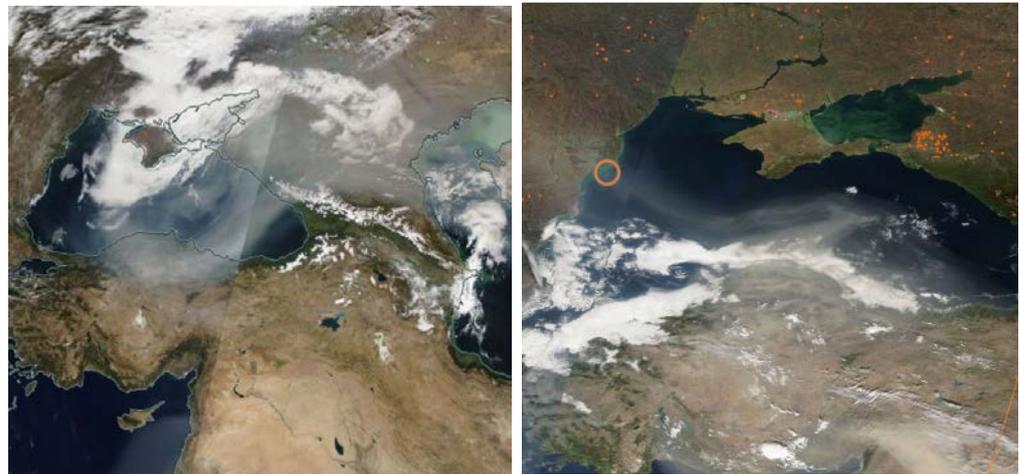
Figure 1. Satellite images from the MODIS Aqua / Terra platforms during dust transport days with a clear visual presence of a dust plume (a) 19.10.2017, (b) 16.10.2018, (c) 14.06.2016, (d) 27.09.2020.

As a mathematical tool, it is proposed to use the method of principal components (PCA) to estimate the spectral features of the change in $Rrs(\lambda)$ in the presence of dust with an estimate of the contribution of the first eigenvector. For a specific task, the difference 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 [33]) (validation error) were taken as a conditional mathematical expectation (Figure 2).

(a)   (b)
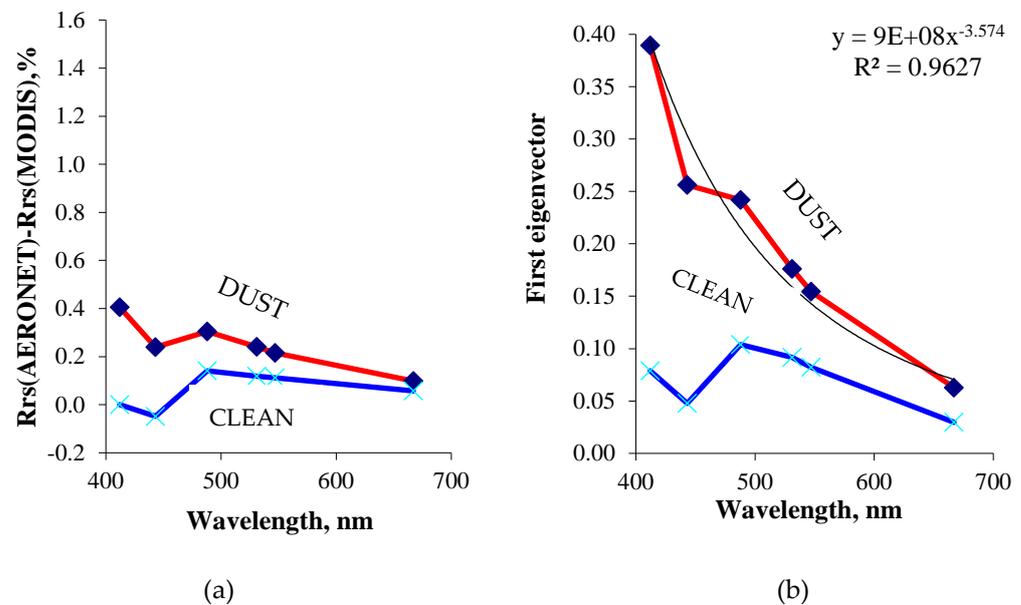
Figure 2. Validation error for Rrs(between MODIS Aqua satellite values and AERONET in situ measurements) for the Black Sea and the first eigenvector of the covariance matrix.

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 the -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 using the 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 the 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 formula (7):

$$Rrs_m(\lambda) = Rrs_{sat}(\lambda) + k \cdot \lambda^{-4} \tag{7}$$

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

$$k = \frac{CI\left(\frac{412}{443}\right)Rrs_{sat}(443) - Rrs_{sat}(412)}{\left(412^{-4} - CI\left(\frac{412}{443}\right)443^{-4}\right)} \tag{8}$$

Thus, assuming k to be constant in the particular case under consideration, using formula (7) 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 measurements from the AERONET Gloria and Galata Platform platforms 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, where the average daily variability was weak). Additionally, Rrs(λ) were tested using the optical three-parameter model. The selected research area is located in the area of complex waters (Case 2), from - due to the influence of river runoff (Dnepr, Dniester, Bug), pronounced summer blooms of coccolithophorids, as well as blooms of diatoms and dinophytes (usually winter period and off-season).[34-37] (Figure 3).
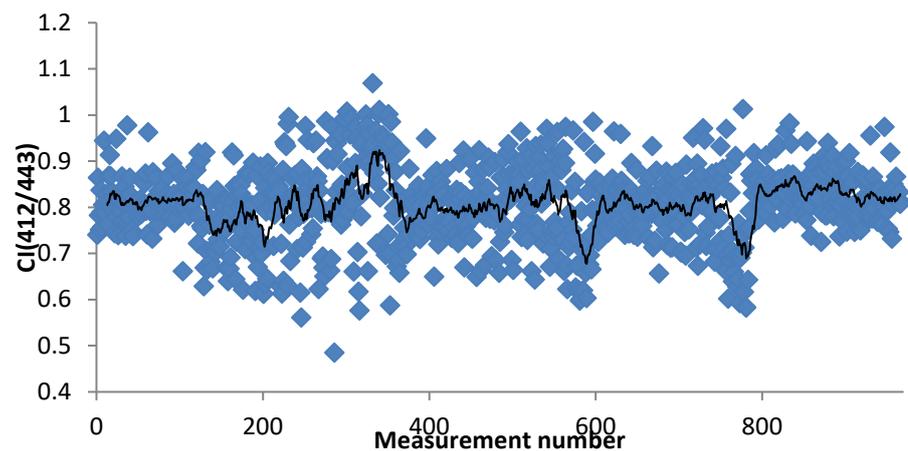

Figure 3. Variability of calculated CI(412/443) values based on in situ data from Gloria and Galata Platform from 2011 to 2022.

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 formula (8) . 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), little variability was observed, RMS values >20%. For the Black Sea region, the correction k can be calculated as:

$$k = \frac{0.8 \cdot Rrs_{sat}(443) - Rrs_{sat}(412)}{(412^{-4} - 0.8 \cdot 443^{-4})}$$

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 (Modis Aqua) was 332 values. For each satellite Rrs(λ), the above method was used to calculate the model values of theremote 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 the cases under consideration (Figure 4).
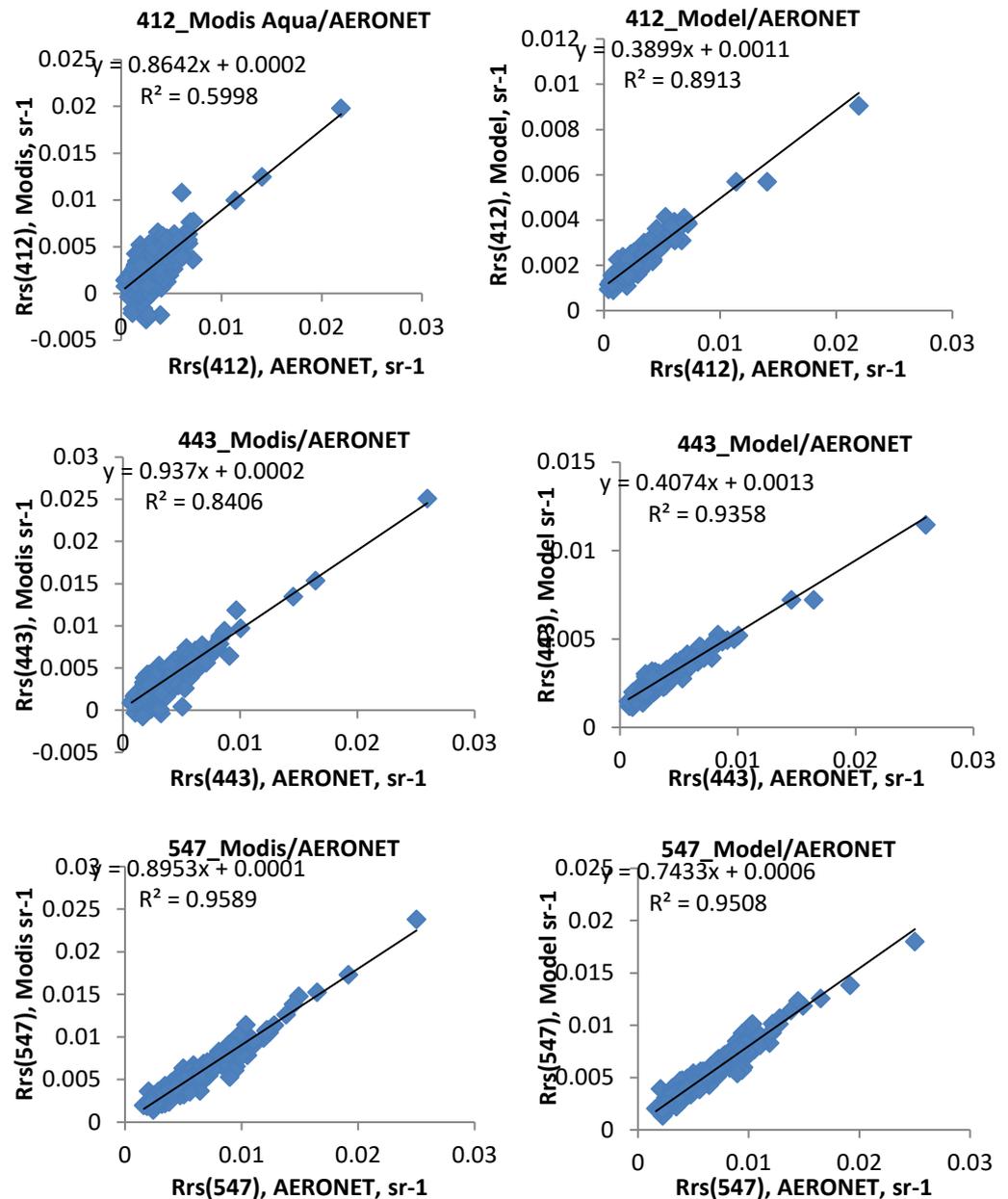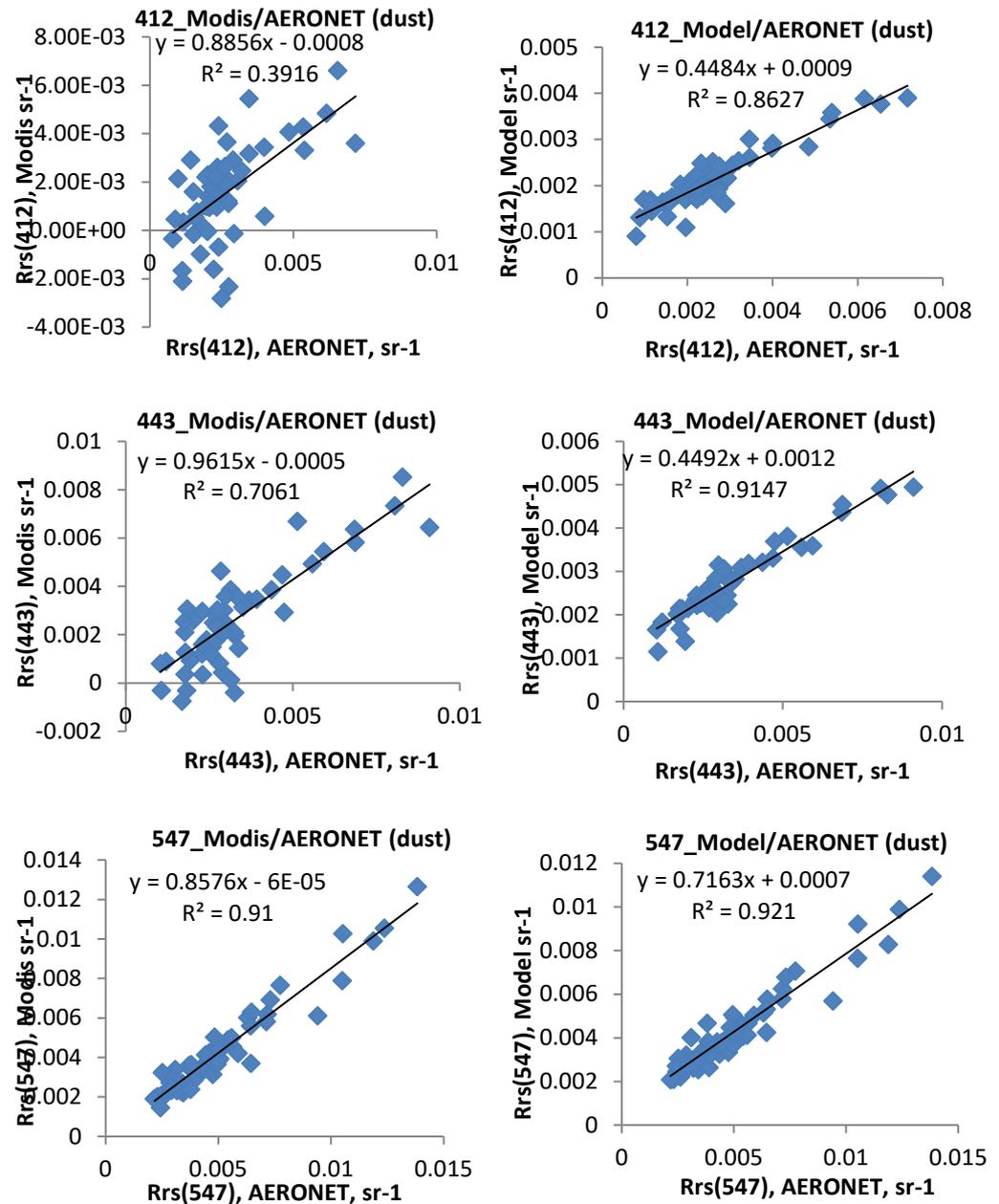

Figure 4. Linear regression of Rrs(λ) between MODIS satellite values and AERONET in situ measurements, as well as model values for the northwestern part of the Black Sea at 412, 443, 488, 547 nm for all cases.

It follows from Figure 4 that the proposed model correction made it possible to bring satellite values closer to reliable ones, especially in the short-wavelength region (412 nm, 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). Models with a determination coefficient above 80% can be considered quite good (the correlation coefficient exceeds 90%).Of particular interest are the cases of the presence of absorbing aerosol; further, 49 cases of the presence of dust over the Black Sea region will be considered. A similar regression analysis was presented separately for the dust case (Figure 5).

Figure 5. Linear regression of Rrs(λ) between MODIS satellite values and AERONET 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 Figure 5 that in the case of the presence of an absorbing aerosol, the developed model increases the coefficient of determination by more than 2 times 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 are in better agreement with in situ data, and if without correction the correlation was 50% (weak), when it was taken into account, it was 70% (noticeable) (Figure 6).
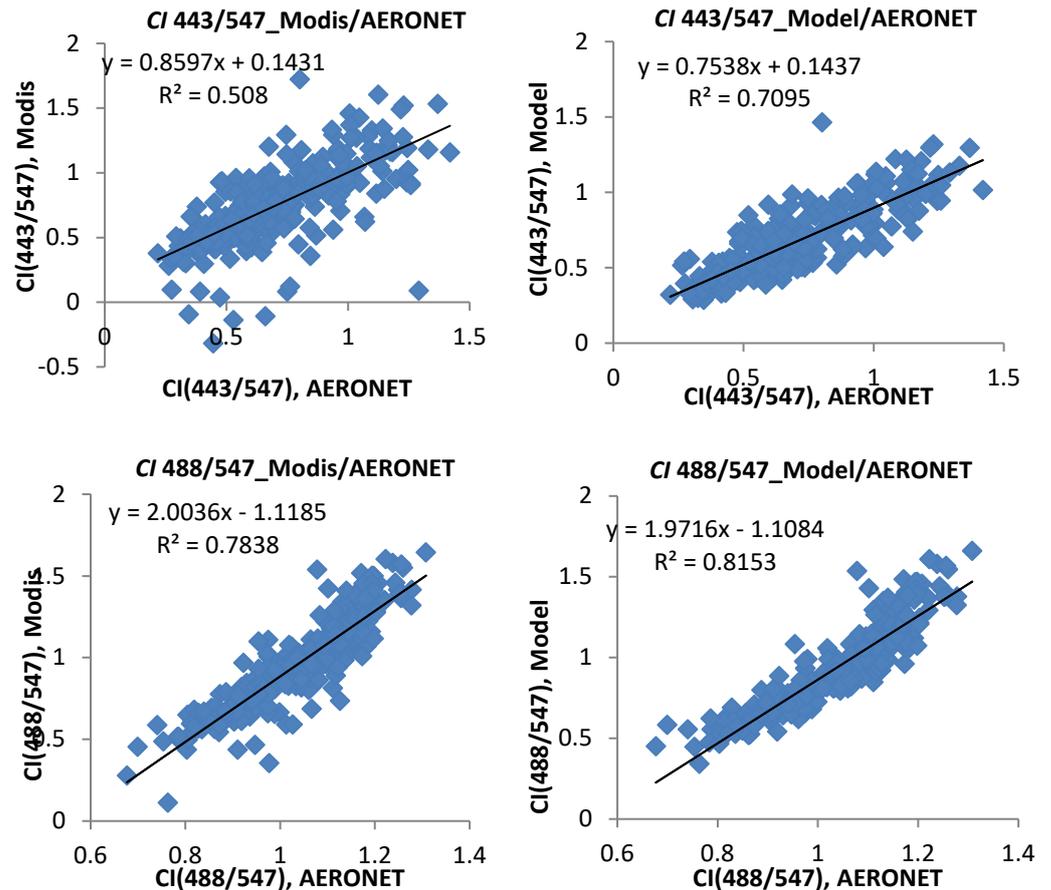

Figure 6. Linear regression of the color index (CI) between MODIS satellite values and AERONET in situ measurements, as well as model values for the northwestern part of the Black Sea

Next, we decided to use an example to consider the principle of restoring color indices. On September 27, 2020, a large-scale dust transport from the Sahara over the Black Sea region was registered (Figure 1(d)). According to Modis Aqua AOT data at 869 nm exceeded the values by 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 incorrect calculation of the color index in Figure 7 (b), sharp jumps in chlorophyll-a were found in the central part of the Black Sea.
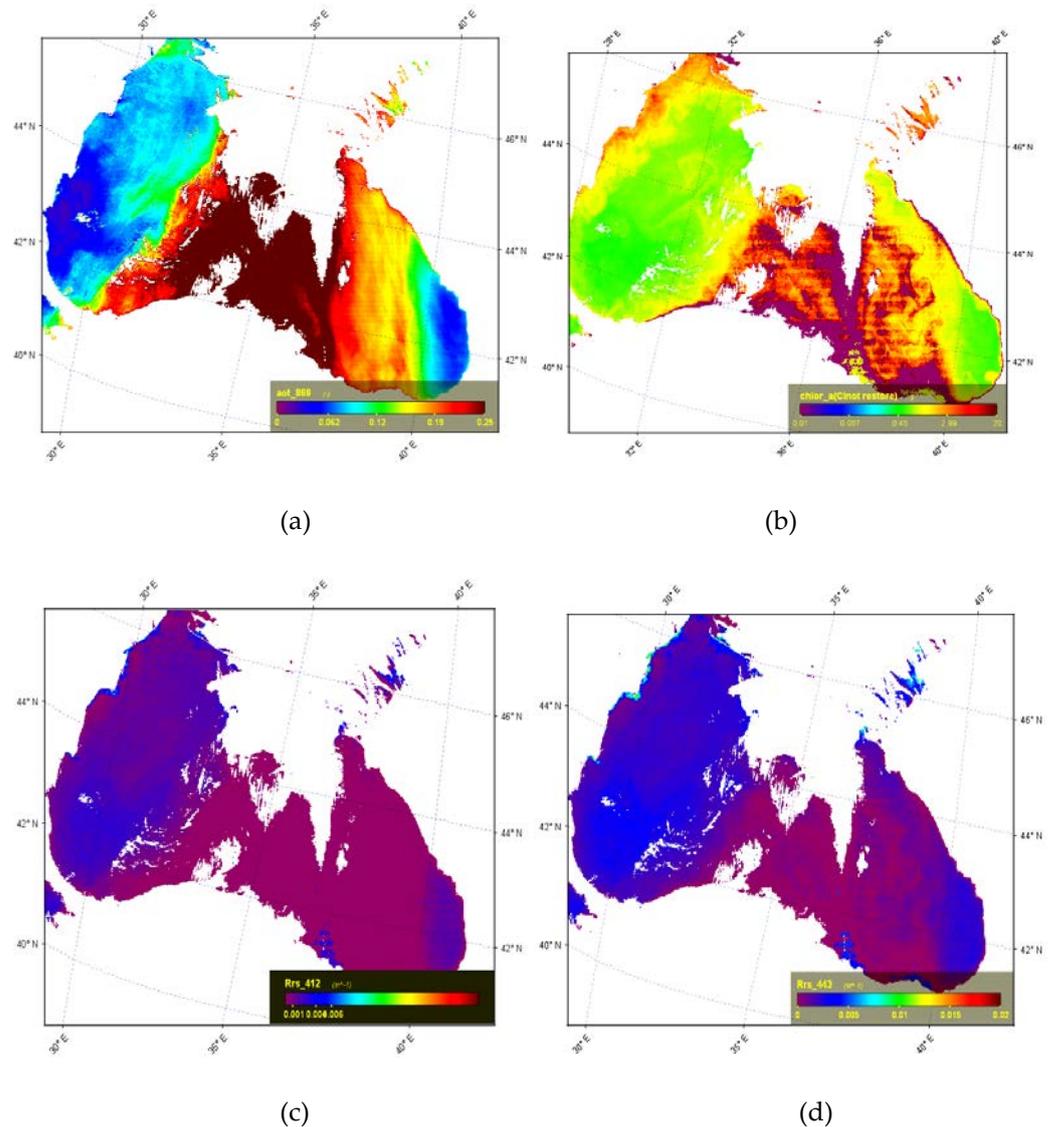
(a)

(b)

(c)

(d)

Figure 7. Analysis of the Modis Aqua satellite image for September 27, 2020: (a) AOT distribution, (b) CI (547/443) ,(c) Rrs(412 nm), (d) Rrs(443 nm) (built in SeaDAS)

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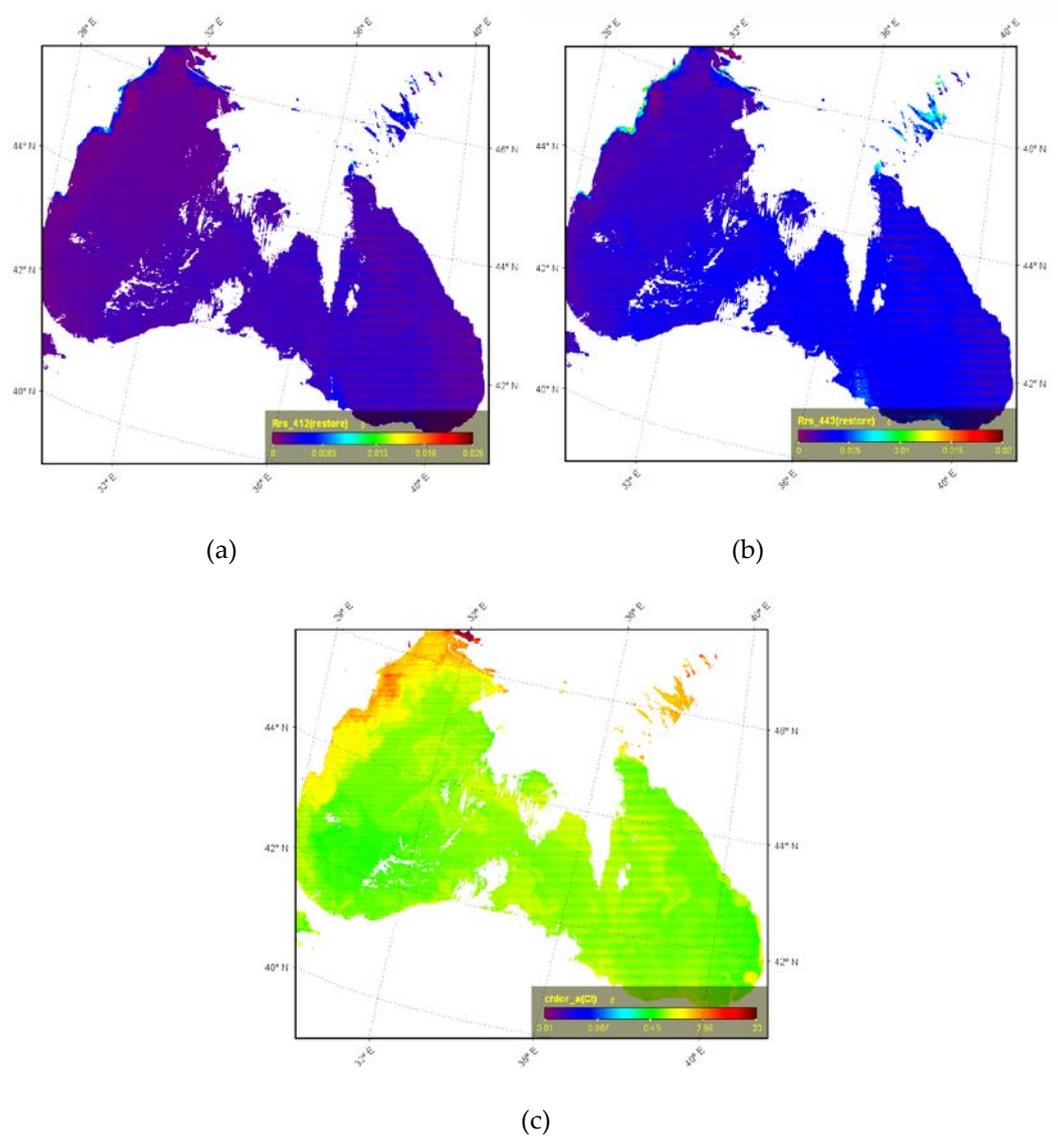
(a)

(b)

(c)

Figure 8. Modis Aqua satellite image data for September 27, 2020, taking into account the model correction: (a) Rrs(412 nm) restored, (b) Rrs(443 nm) restored, (c) CI(547/443) restored (built in SeaDAS)

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, in the case of 12.07.2020, the satellite image from Modis Aqua, 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 applying the new model correction, the data did not change, there are no obvious distortions (Figure 9).
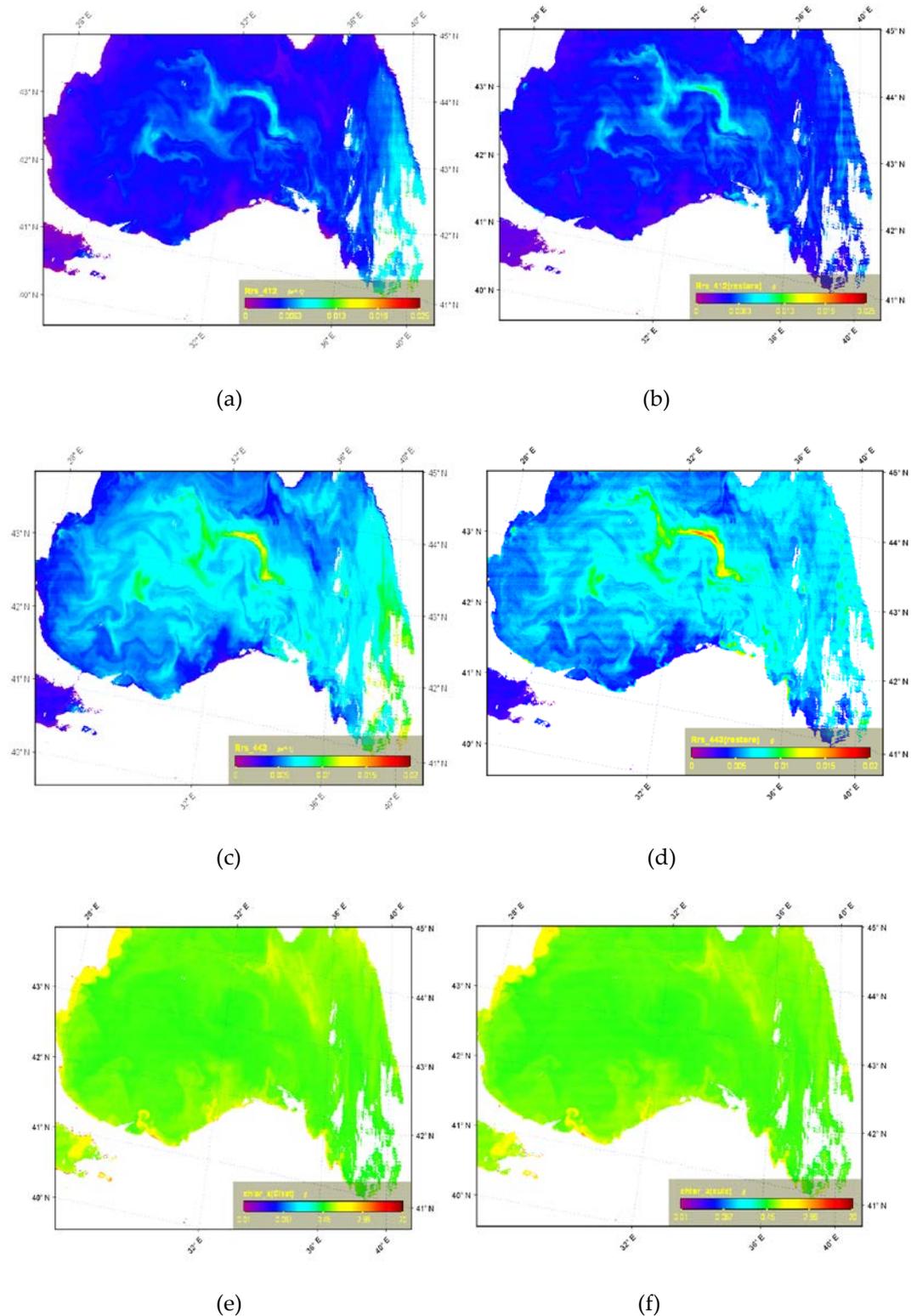
(a)

(b)

(c)

(d)

(e)

(f)

Figure 9. Modis Aqua satellite image data for July 12, 2020, taking into account the model correction: (a) Rrs(412 nm), (b) Rrs(412 nm) restored, (c) Rrs(443 nm) , (d) Rrs(443 nm) restored, (e) Chl_a, (f) Chl_a restored (built in SeaDAS)

After considering many cases, we concluded possible to use this model correction even in the absence of absorbing aerosol, even in cases of phytoplankton blooms.

4. Discussion

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 describing 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, 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 an absorbing aerosol, the atmospheric correction error is described by the spectral course of molecular scattering, i.e. close to λ^{-4}. This is due to the absorption of the aerosol component of the molecular component. 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 $Rrs(\lambda)$, the principal component method (PCA) was used for 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 satellite and 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 an 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 using the infrared channel , however, the arid aerosol has the main influence on the ratio of the 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 $Rrs(\lambda)$ 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 $Rrs(\lambda)$ at level 2. In the case of the presence of an absorbing aerosol, the developed model increases the coefficient of determination R^2 between the satellite and in situ values of $Rrs(\lambda)$ by more than 2 times at 412 nm , the difference is also noticeable at 443 and 488 nm, in the green range 531-555 nm the changes are insignificant. The color indices calculated from the model values of $Rrs(\lambda)$, which are necessary for calculating Chl-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 in color indices. The big advantage of the developed algorithm is its simplicity in implementation, the possibility of using even in the absence of dust without data distortion, a small set of input parameters.

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environment and mathematical modeling with the use of data from remote and contact measurements" (code "Operational Oceanology").

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