

Article

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

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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 color index at 412 and 443 nm (CI(412/443)) approximately equals to  $0.80 \pm 0.08$ , 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 remote sensing reflectance.

**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  $L_w(\lambda)$  [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 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, the contribution due to aerosols and from surface whitecaps and foam, the water-leaving component, also glint and residual cloud have a contribution). 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  $R_{rs}(\lambda)$  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 to 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  $\lambda$  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 nm 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 SOA spectral optimization algorithm [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 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 [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 (for example 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 approximately intersect in the vicinity of 510 nm. If the variability of

$R_{rs}(510)$  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 original definition of Case-1 and Case-2 waters was from Morel and Prieur [16]. 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  $R_{rs}(\lambda)$  spectrum cannot be arbitrary. For the Black Sea, the following methods of parameterization of remote sensing reflectance were proposed: negligible of  $R_{rs}(\lambda)$  values in the near ultraviolet and constancy of values in the "blue" short-wavelength region [18, 19], estimation of the value of  $R_{rs}(412)$  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 the global network of observation ground automated stations (platforms) 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 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 (44.45°N, 29.45°E). The water depth in both places is about 40 m. The Galata\_Platform AERONET-OC site, 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. 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 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  $Rrs(\lambda)$  by dividing by the solar constant  $S_0(\lambda)$ .

### 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 are designed to study the atmosphere and 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  $\mu\text{m}$ . 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. 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 ( $Rrs(\lambda)$ ) ( $\text{sr}^{-1}$ ), for MODIS data is determined for spectral channels 412, 443, 469, 488, 531, 547, 555, 645, 667, 678 nm. The concentration of chlorophyll a, ( $\text{mg m}^{-3}$ ) according to MODIS data is calculated using  $Rrs(\lambda)$  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 should reflect the physical meaning of light propagation in an inhomogeneous absorbing medium and have the simplest solutions to the radiative transfer equation in particular cases, solutions corresponding to well-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  $T^u(z)$  is the attenuation of the radiation scattered by the added layer in the opposite direction.

$$\frac{dR}{dz} = T^d(z) \cdot T^u(z) \cdot \frac{b(z)p(z, \cos \gamma)}{4\mu_1\mu_2} \quad (1)$$

$$\cos \gamma = -\mu_1\mu_2 + \sqrt{1 - \mu_1^2} \sqrt{1 - \mu_2^2} \cos \varphi$$

Where  $b(z)$  is the total scattering (aerosol+Rayleigh) at the depth  $z$ ,  $p(\cos \gamma)$  is the phase function depending on scattering angle  $\gamma$ ;  $\mu_1, \mu_2$  – are the cosine of the zenith angle of incidence onto an infinitely thin layer and the cosine of the zenith angle of reflection from an infinitely thin layer;  $\varphi$  – difference of azimuths, azimuth of observation angle and azimuth of the Sun.

Assume that  $\tau$  – 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  $\mu_0, \mu$  are the cosines of the zenith angles of the Sun and the observation angle, we obtain the estimate  $\mu_1 \approx \mu_0, \mu_2 \approx \mu$ . In this case, it is proposed to use analytical expressions for the transmission functions  $T^d(z)$ .

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

$$a(z) = \frac{d\tau_a(z)}{dz} \cdot (1 - \Lambda(z))$$

where  $a(z)$  – vertical profile of the aerosol absorption;  $\tau_a(z)$  is aerosol optical depth from the top of atmosphere up to depth  $z$ ;  $\Lambda(z)$  – 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:

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

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 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 (3) can be written as:

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

$$a_0(\lambda) = (1 - \Lambda) \tau_a^0$$

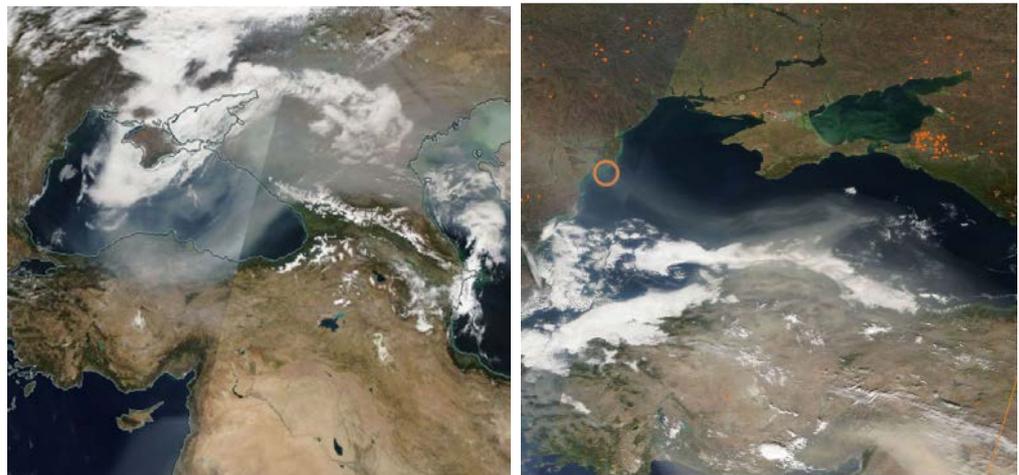
where  $g(z)$  – power function of aerosol stratification,  $\tau_a^0$  – AOT,  $\tau_m^0$  – is the total optical thickness of the molecular atmosphere and  $a_0$  – optical thickness of aerosol absorption. It is worth noting that formula (4) is suitable for any possible distribution in height. In the case of exponential height dependences of aerosol and molecular scattering power function of aerosol stratification can be calculated as:

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

where  $h_m \approx 8 \text{ km}$ ,  $h_a \approx 1.2 \text{ km}$  – 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 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  $\lambda^{-4}$ .

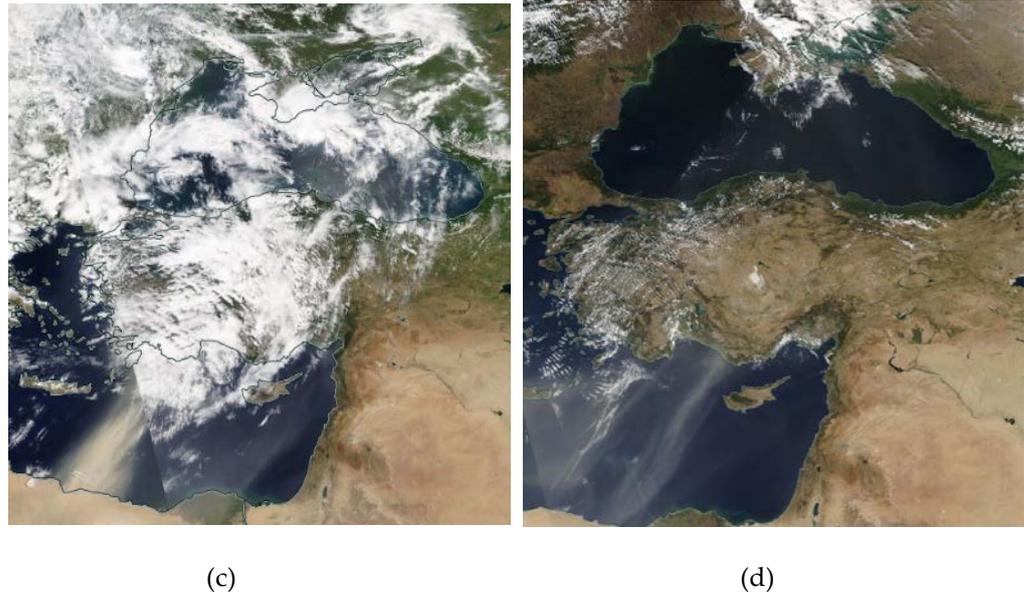
#### 4. Results

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 validation of satellite (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 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 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 Figure 1.



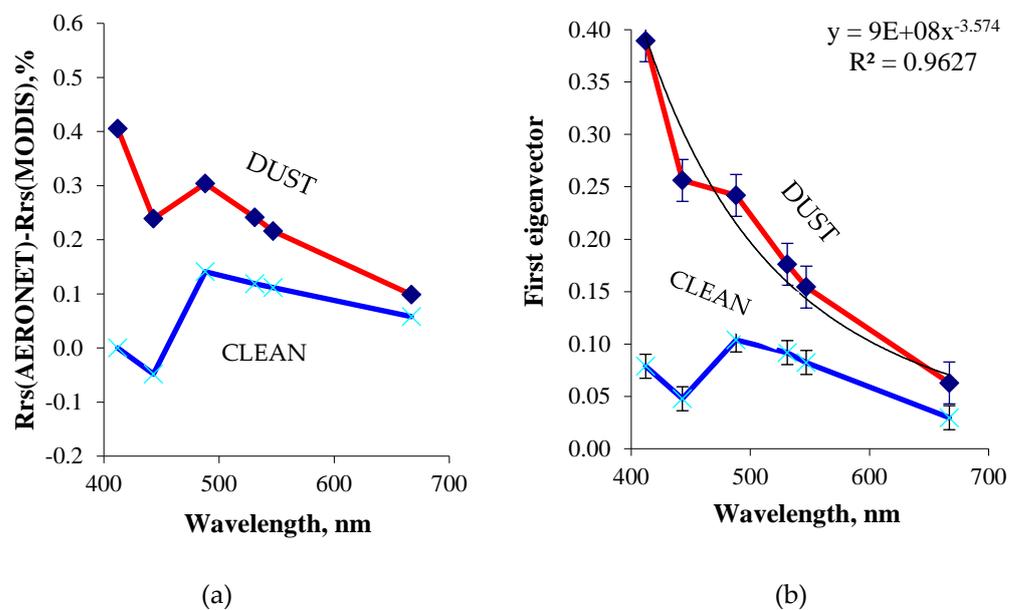
(a)

(b)



**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 [28]) (validation error) were taken as a conditional mathematical expectation (Figure 2).



**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 the remote 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  $Rrs(\lambda)$  will be calculated by linear regression formula (5):

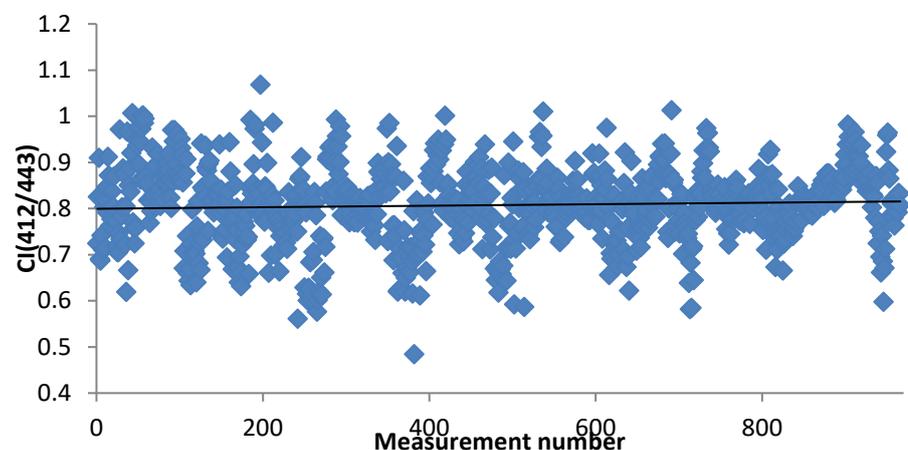
$$Rrs_m(\lambda) = Rrs_{sat}(\lambda) + k\lambda^{-4} \quad (5)$$

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 color index (CI) for these two channels, calculated from the analysis of in situ measurements.

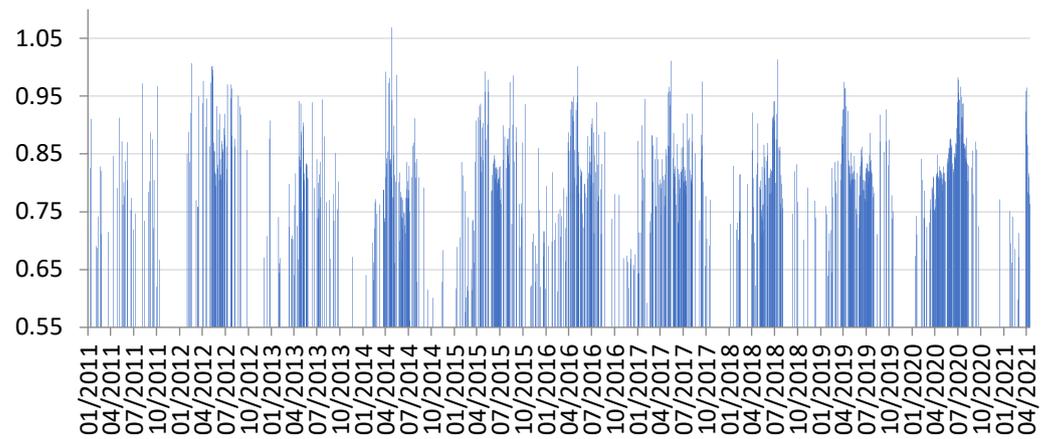
$$k = \frac{CI\left(\frac{412}{443}\right)Rrs_{sat}(443) - Rrs_{sat}(412)}{(412^{-4} - CI\left(\frac{412}{443}\right)443^{-4})} \quad (6)$$

Thus, assuming  $k$  to be constant in the particular case under consideration, using formula (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 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  $Rrs(\lambda)$  (averaged values per day). It was proposed to analyze the average daily values of the  $Rrs(\lambda)$  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 the  $Rrs(\lambda)$  for the same day at 412 nm should not exceed 10%. The selected research area is located in the area of complex waters (Case 2), 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).[29-32] (Figure 3).



(a)

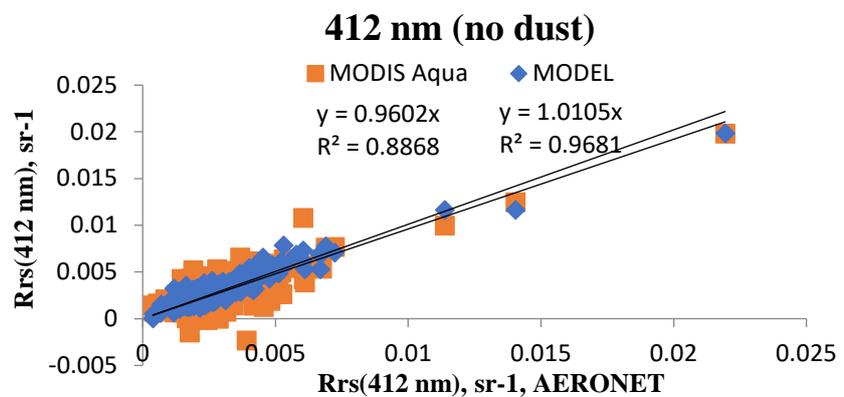


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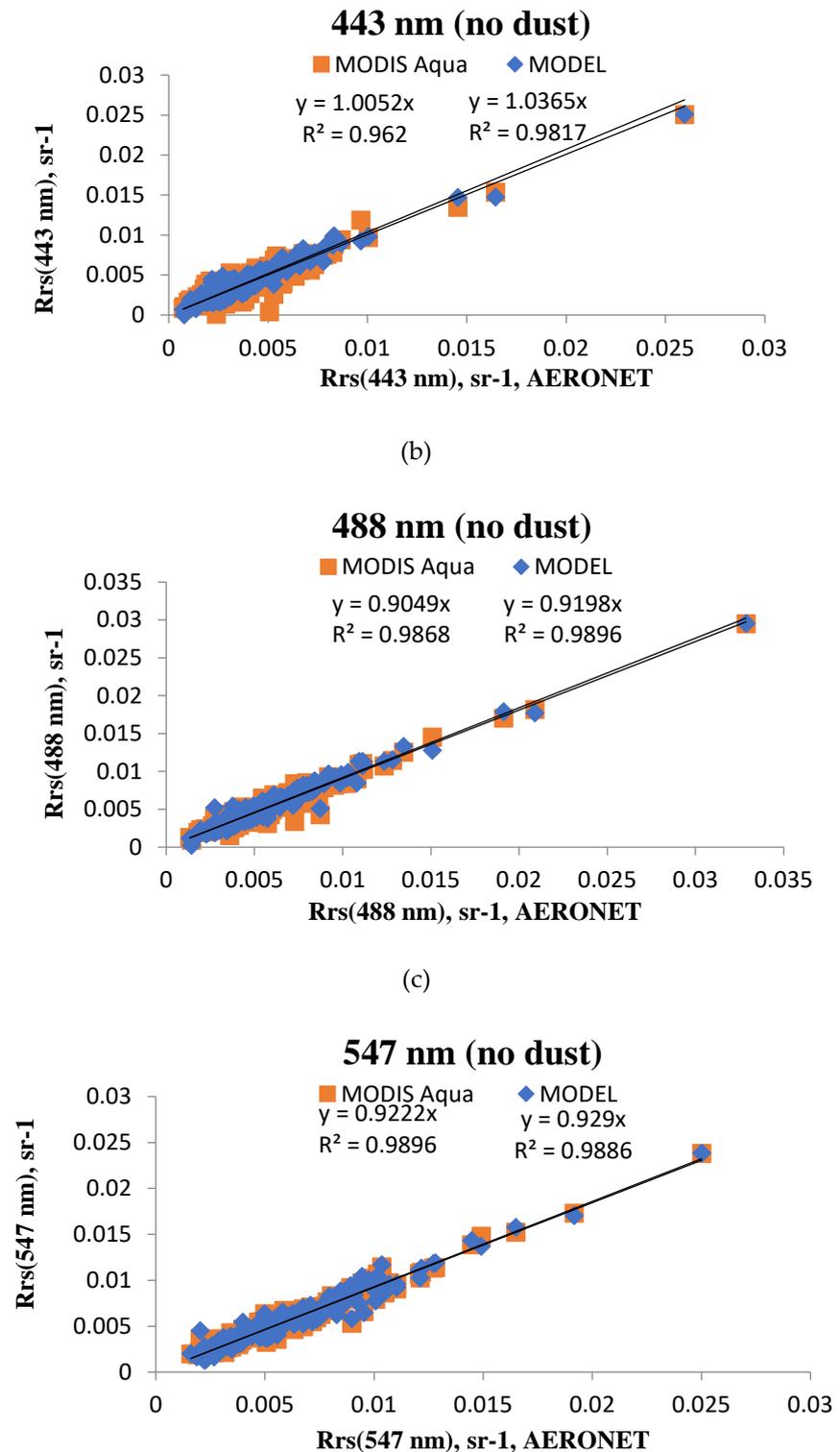
**Figure 3.** (a) Variability of calculated CI(412/443) values based on in situ data from Gloria and Galata Platform from 2011 to 2022; (b) Seasonality of CI(412/443).

The black line on the Fig. 3 shows a linear trend. The average value of  $CI(412/443) = 0.80 \pm 0.08$ , 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 (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  $>20\%$ . For the Black Sea region, the correction  $k$  can be calculated by substituting  $CI(412/443)=0.8$  into Eq 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 (MODISAqua) was 332 values. For each satellite  $Rrs(\lambda)$ , 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 cases where is no dust detected (Figure 4).



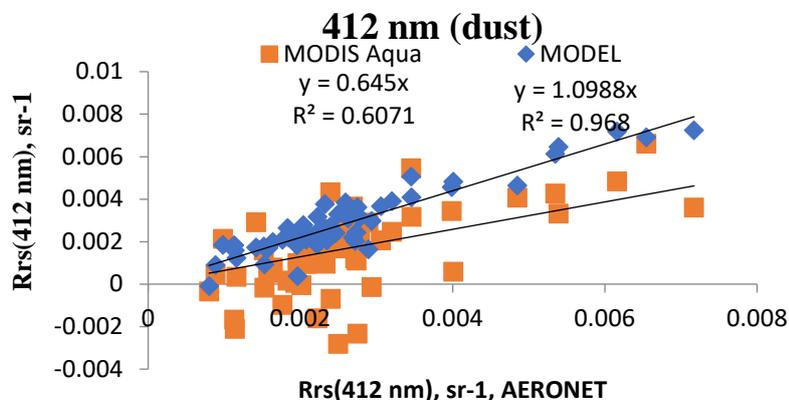
(a)



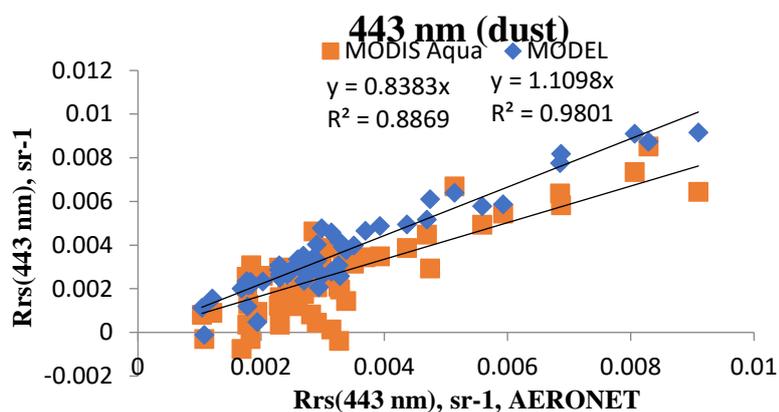
**Figure 4.** Linear regression of  $Rrs(\lambda)$  between MODIS satellite values and AERONET in situ measurements, as well as model values for the northwestern part of the Black Sea at 412, 443, 488, 555 nm for all cases where no dust is detected.

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

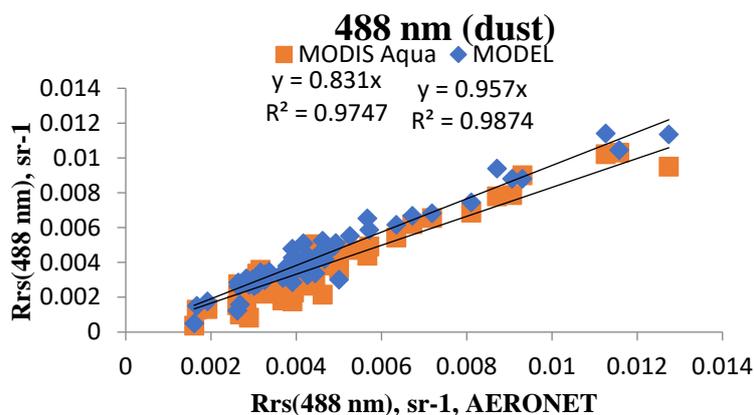
quite good (the correlation coefficient exceeds 90%). Of particular interest are the cases of the presence of absorbing aerosol; further, 49 cases of the presence of dust over the Black Sea region will be considered. A similar regression analysis was presented separately for the dust case (Figure 5).



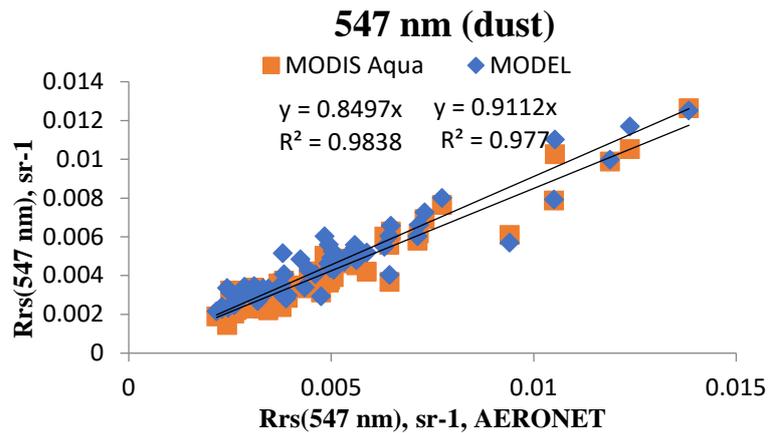
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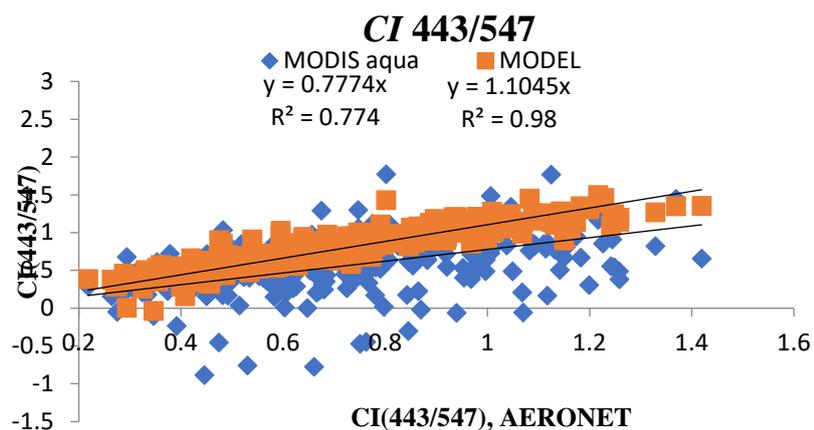


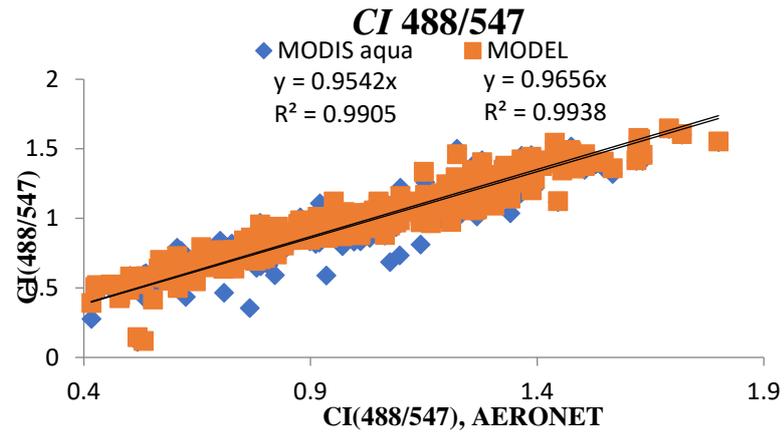
(c)



**Figure 5.** Linear regression of  $Rrs(\lambda)$  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.

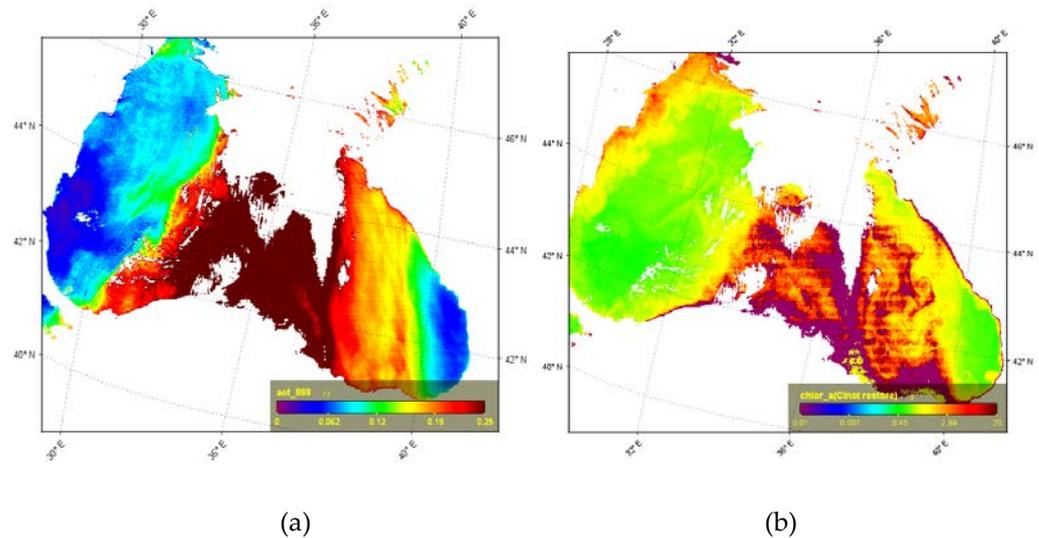
It follows from Figure 5 that in the case of the presence of an absorbing aerosol, the developed model increases the coefficient of determination by more than 2 times at 412 nm, the difference is also noticeable at 443 and 488 nm, in the green range of 531-555 nm the changes are insignificant. This algorithm 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).

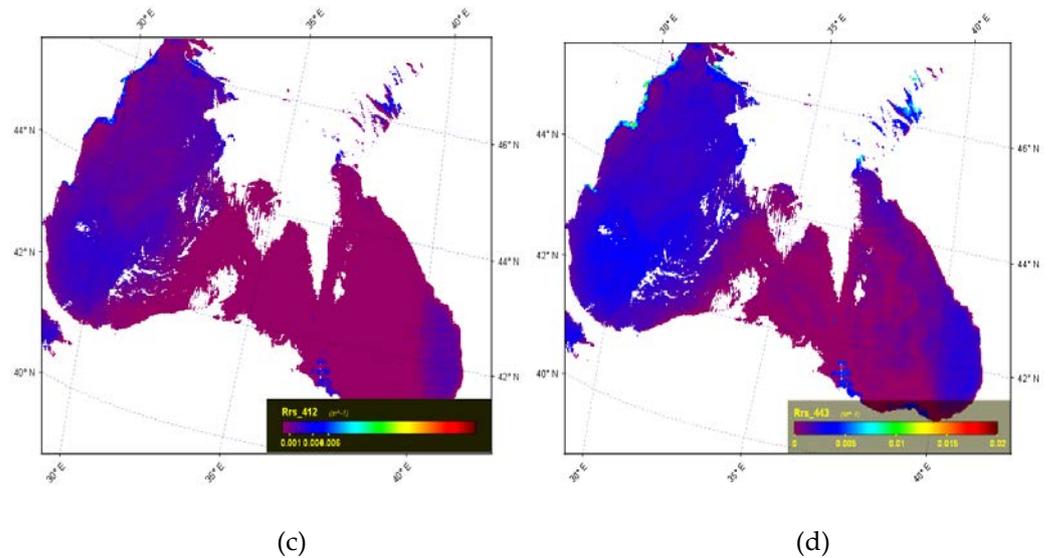




**Figure 6.** Linear regression of the color index (CI) between MODIS satellite values and AERONET in situ measurements, as well as model values for the northwestern part of the Black Sea

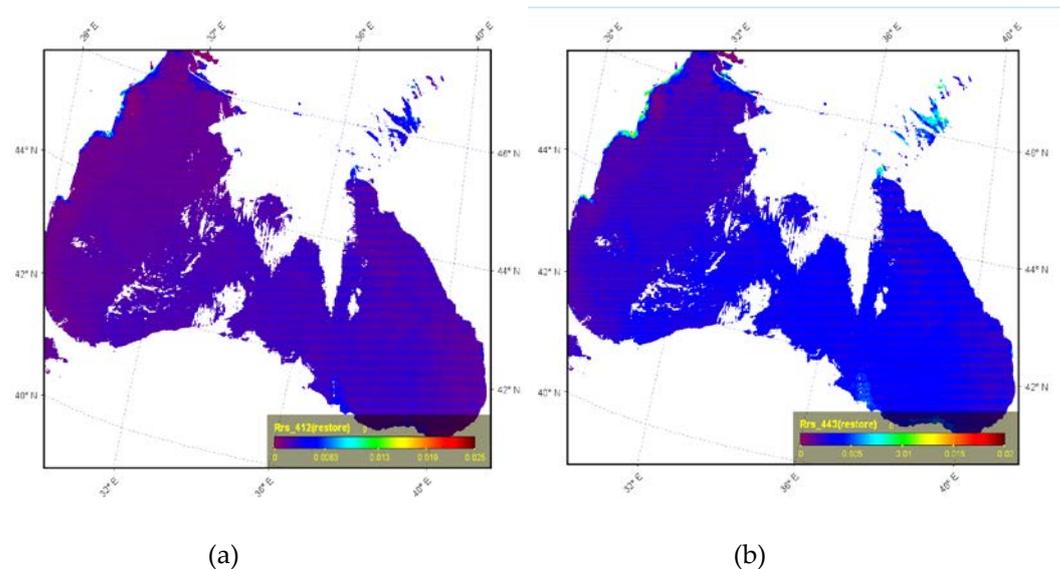
Next, we decided to use an example to consider the principle of restoring color indices. On September 27, 2020, a large-scale dust transport from the Sahara over the Black Sea region was registered (Figure 1(d)). According to MODIS Aqua AOT data at 869 nm exceeded 0.25 in the central part of the Black 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.

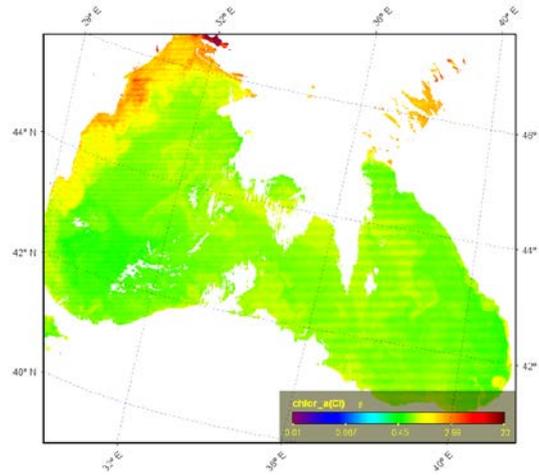




**Figure 7.** Analysis of the MODIS Aqua satellite image for September 27, 2020: (a) AOT distribution, (b) CI (547/443) ,(c) Rrs(412 nm), (d) Rrs(443 nm) (built in SeaDAS)

Using the new model correction, we recalculated all  $Rrs(\lambda)$  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 bloom in the central part, it was found that there was no bloom 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.

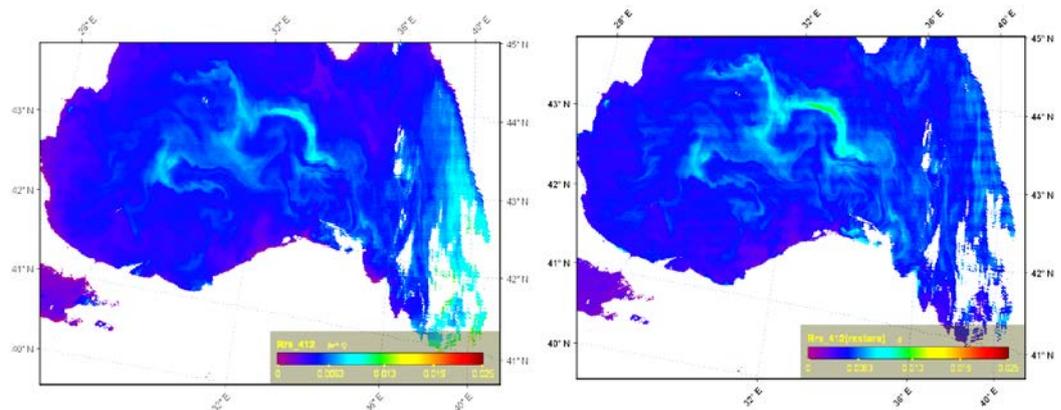




(c)

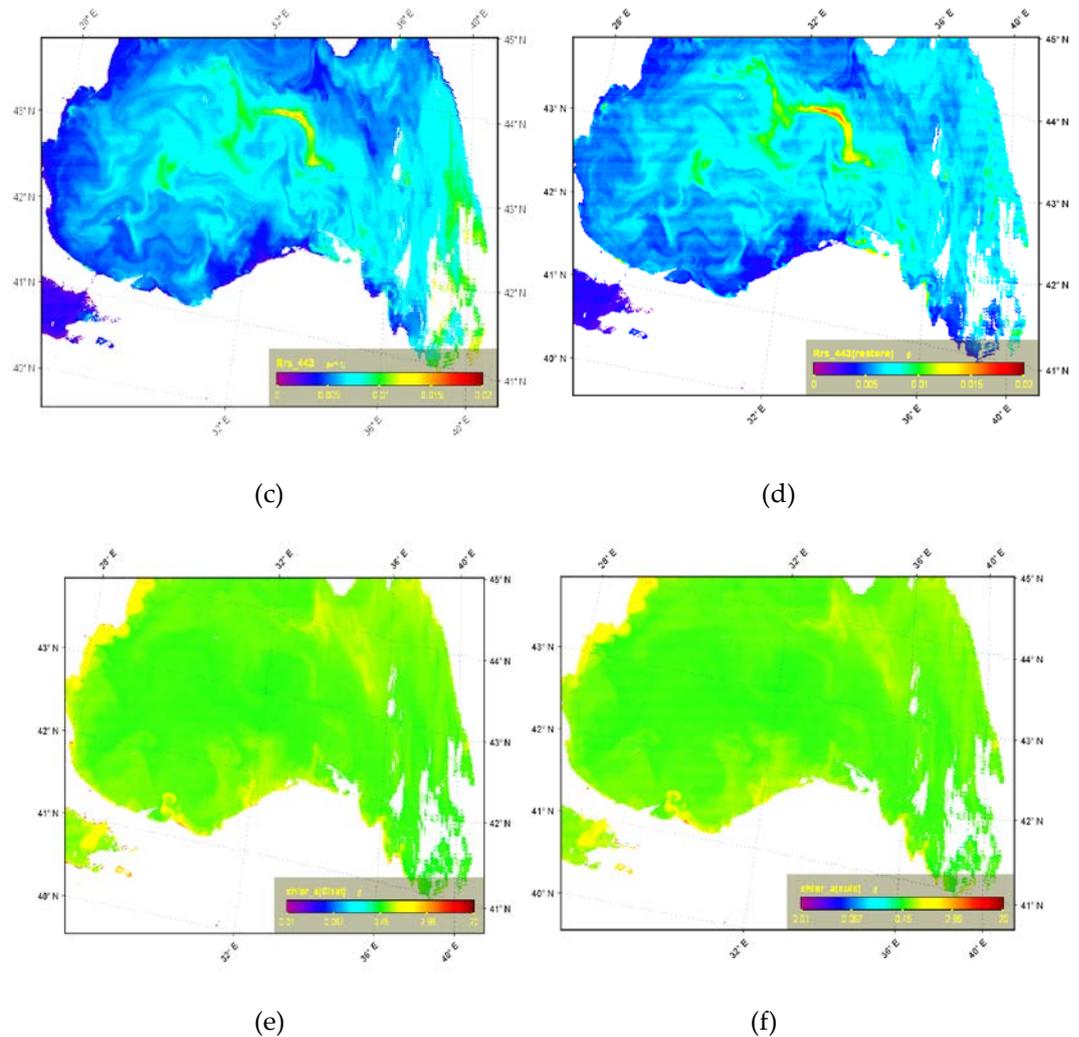
**Figure 8.** MODIS Aqua satellite image data for September 27, 2020, taking into account the model correction: (a) Rrs(412 nm) restored, (b) Rrs(443 nm) restored, (c) CI(547/443) restored (built in SeaDAS)

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 small 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)



**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  $\lambda^{-4}$ . 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 systematic 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  $0.80 \pm 0.08$ . 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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**Data Availability Statement:** The data presented in this study are available on request from the corresponding author.

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## References

1. Werdell, P. J.; Bailey, S. W. An improved bio-optical data set for ocean color algorithm development and satellite data product validation. *Remote Sensing of Environment* **2005**, V.98, pp. 122-140, <https://doi.org/10.1016/j.rse.2005.07.001>
2. Gordon, H.R. Evolution of Ocean Color Atmospheric Correction:1970–2005. *Remote Sens.* **2021**, *13*, 5051. <https://doi.org/10.3390/rs13245051>
3. Thuillier, G., Hersé, M., Labs, D., et al. (2003). The solar spectral irradiance from 200 to 2400 nm as measured by the SOLSPEC spectrometer from the Atlas and Eureca missions. *Solar Physics* **214**: 1. doi:10.1023/A:1024048429145
4. Viollier, M. Radiance calibration of the Coastal Zone Color Scanner: A proposed adjustment. *Appl. Opt.* **1982**, *21*, 1142–1145.
5. Gordon, H.R. Can the Lambert-Beer law be applied to the diffuse attenuation coefficient of ocean water. *Limnology and Oceanography* **1989**, V. *34*, No. *8*, pp. 1389-1409.
6. Deschamps, P.Y.; Herman, M.; Tanre, D. Modeling of the atmospheric effects and its application to the remote sensing of ocean color. *Appl. Opt.* **1983**, *22*, 3751–3758
7. Gordon, H.R.; Wang, M. Retrieval of water-leaving radiance and aerosol optical thickness over the oceans with SeaWiFS: A preliminary algorithm. *Appl. Opt.* **1994**, *33*, 443–452.
8. Korchemkina, E.N.; Shibanov, E.B.; Li, M.E. Improvement of the Atmospheric Correction Technique for Remote Investigations of Black Sea Coastal Waters. *Issled. Earth from space* **2009**, V. *6*, pp. 24–30.
9. Lee S., Meister G. MODIS Aqua Optical Throughput Degradation Impact on Relative Spectral Response and Calibration of Ocean Color Products // *IEEE Trans. Geoscience and Remote Sensing*. **2017**. V. *55*. P. 5214–5219. <https://doi.org/10.1109/TGRS.2017.2703672>.
10. Kalinskaya, D.V.; Papkova, A.S. Why Is It Important to Consider Dust Aerosol in the Sevastopol and Black Sea Region during Remote Sensing Tasks? A Case Study. *Remote Sens.* **2022**, *14*, 1890. <https://doi.org/10.3390/rs14081890>
11. Suetin, V.S; Korolev, S.N. Application of Satellite Data for Retrieving the Light Absorption Characteristics in the Black Sea Waters. *Physical Oceanography* **2021**, V. *28*(2), pp. 205-214. <https://doi.org/10.22449/1573-160X-2021-2-205-214>
12. Omar A.H., Winker D., Vaughan M., Hu Y., Trepte C., Ferrare R., Lee P., Hostetler C., Kittaka C., Rogers R., Kuehn R., The CALIPSO Automated Aerosol Classification and Lidar Ratio Selection Algorithm, *J. Atmospheric and Oceanic Technology*, **2009**, Vol. *26*, pp. 1994–2014, <https://doi.org/10.5194/amt-11-6107-2018>
13. Gordon, H.R.; Du, T.; Zhang, T. Remote sensing of ocean color and aerosol properties: Resolving the issue of aerosol absorption. *Appl. Opt.* **1997**, *36*, 8670–8684
14. Chomko, R.; Gordon, H.R. Atmospheric correction of ocean color imagery: Use of the Junge power-law aerosol size distribution with variable refractive index to handle aerosol absorption. *Appl. Opt.* **1998**, *37*, 5560–5572
15. Antoine, D.; Morel, A. A multiple scattering algorithm for atmospheric correction of remotely sensed ocean color (MERIS instrument): Principle and implementation for atmospheres carrying various aerosol including absorbing ones. *Int. J. RemoteSens.* **1999**, *20*, 1875–1916.
16. Morel, A.; Prieur, L. Analysis of variations in ocean color. *Limnol. Oceanogr.* **1977**, *22*, 709–722.
17. Themistocleous, K.; Papoutsas, C.; Michaelides, S.; Hadjimitsis, D. Investigating Detection of Floating Plastic Litter from Space Using Sentinel-2 Imagery. *Remote Sens.* **2020**, *12*, 2648. <https://doi.org/10.3390/rs12162648>
18. Parshikov S.V., Li M.E. Remote sensing of optically active impurities using the short-wavelength part of the spectrum // Automated systems for monitoring the state of the marine environment - Sevastopol, MGI NAS of Ukraine, 1992.–P.65-78K.Ya. Kondratiev, D.V. Pozdnyakov Aerosol models of the atmosphere / M.: Nauka, 1981. - 104 p.
19. Shibanov E.B., Korchemkina E.N. Reconstruction of the biooptical characteristics of the Black Sea waters under the condition of a constant brightness coefficient at a wavelength of 400 nm // *Marine Hydrophysical Journal*. - 2008. - No. 1. - P. 38–50.
20. Smirnov, A.; Holben, B.N.; Slutsker, I.; Giles, D.M.; McClain, C.R.; Eck, T.F.; Sakerin, S.M.; Macke, A.; Croot, P.; Zibordi, G.; et al. Maritime Aerosol Network as a component of Aerosol Robotic Network. *J. Geophys. Res.* **2009**, *114*, 204.
21. Zibordi, G.; Holben, B.; Slutsker, I.; Giles, G.; D'Alimonte, D.; Melin, F.; Berthon, J. F.; Vandemark, D.; Feng, H.; Schuster, G.; Fabbri, B. E.; Kaitala, S.; and Seppala, J. AERONET-OC: A Network for the Validation of Ocean Color Primary Products. *J. Atmos. and Oceanic Technology* **2009**, V. *26*, 1634-1651, <https://doi.org/10.1175/2009JTECHO654.1>
22. O'Reilly, J.E., Maritorena, S., Mitchell, B. G., Siegel, D. A., Carder, K. L., Garver, S. A., Kahru, M., & McClain, C. R. (1998). Ocean color chlorophyll algorithms for SeaWiFS, *Journal of Geophysical Research* **103**, 24937-24953, doi: 10.1029/98JC02160.
23. Morel, A., Maritorena, S. (2001). Bio-optical properties of oceanic waters: A reappraisal. *Journal of Geophysical Research: Oceans*, **106**(C4), 7163-7180. doi: 10.1029/2000jc000319
24. Preisendorfer R.W. Hydrologic Optics / R.W. Preisendorfer // VOLUME II, Chapter 3, The Interaction Principle, Joint Tsunami Research Effort, Honolulu Hawaii, U.S. Department of Commerce, NOAA, Environmental Research Laboratories, Pacific Marine Environmental Laboratory, 1976. - P. 188–400.
25. Plass G.N. Matrix Operator Theory II. Scattering from Maritime Haze G.N. Plass, G.W Kattawar., F.E. Catchings // *Appl. Opt.* - **1973**. - Vol. *12*. - P. 1071–1084.
26. Shibanov E.B. Numerical method for the solution of the equation of radiation transfer. Reflection and transmission coefficients for an optically thin plane-parallel layer / E.B. Shibanov // *Physical Oceanography*. - **2005**. - V. *15*, Issue *3*. - P. 192–202. doi: 10.1007/s11110-005-0041-2.

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27. Schoeberl, M. R., and P. A. Newman, A multiple-level trajectory analysis of vortex filaments, *J. Geophys. Res.*, 100, 25,801-25,816, 1995.
  28. P.J. Werdell, S.W. Bailey, G.S. Fargion, C. Pietras, K.D. Knobelspiesse, G.C. Feldman, and C.R. McClain, "Unique data repository facilitates ocean color satellite validation", *EOS Trans. AGU* 84 , 38, 377 (2003)
  29. Kopelevich, O.V.; Sheberstov, S.V.; Yunev, O.; Basturk, O.; Finenko, Z.Z.; Nikonov, S.; Vedernikov, V.I. Surface chlorophyll in the Black Sea over 1978-86 derived from satellite and in situ data. *J. Mar. Systems* 2002, V. 36, No. 3-4, pp. 145-160.
  30. Zibordi, G.; Mélin, F.; Berthon, J.F.; Talone M. In situ autonomous optical radiometry measurements for satellite ocean color validation in the Western Black Sea. *Ocean Sci.* **2015**, V.11, pp. 275-286, 10.5194/os-11-275-2015
  31. . Stagl, J.C.; Hattermann, F.F. Impacts of Climate Change on the Hydrological Regime of the Danube River and Its Tributaries Using an Ensemble of Climate Scenarios. *Water* 2015, 7, 6139-6172. <https://doi.org/10.3390/w7116139>
  32. Kopelevich, O.V.; Burenkov, V.I.; Sheberstov, S.V.; Vazyulya, S.V.; Kravchishina, M.D.; Pautova, L.; Silkin, V.A.; Artemiev, V.A.; Grigoriev V. Satellite monitoring of coccolithophore blooms in the Black Sea from ocean color data. *Remote Sensing of Environment* 2014, V. 146, pp. 113–123.