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Original article

Variability of the Water-Leaving Radiance under the Conditions of Dust Transport by the Satellite *Sentinel*-3 Data on the Example of the Black Sea and Sevastopol

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Purpose. The meteorological situation in November 2021 has resulted in forming the conditions for intensive dust aerosol transfer to the Black Sea region. Intensive precipitation has contributed to the subsequent deposition of dust particles on the Black Sea surface layer and in its coastal zone. The work is purposed at comprehensive studying the case of abnormally intense precipitation in Sevastopol with a storm wind speed up to 27 m/s for November 29–30, 2021 using satellite and ground-based monitoring means for assessing the aerosol impact on the sea and atmosphere optical characteristics in the region under study.
Methods and Results. For November 29 and 30, 2021, the calculated concentrations of PM10 and PM2.5 particles were measured in the atmosphere over Sevastopol by the ATMAS dust meter. To determine the source of aerosol transport by means of a cyclone, the results of calculating the back trajectories of air mass transfer were analyzed. The trajectories were obtained using the HYSPLIT and AERONET models software package for Sevastopol. Comprehensive analysis of satellite and field data has resulted in recording the atmospheric aerosol transfer by dust. A comparative analysis of the data on concentrations of the PM10, PM2.5 particles and dust based on the SILAM model and field data, confirmed the dust aerosol transfer from Africa to the Black Sea region. The data of the WRF (Weather and Research Forecasting) modeling of the transfer event on 29.11.2021 testify to the fact that in the western part of the Black Sea, the concentration of dust particles was up to 2000 $\mu g/m^{-3}$ (in the same part of the sea, before the dust transfer, the dust concentration did not exceed 50 $\mu g/m^{-3}$). On 30.11.2021, the dust plume shifted to the eastern region. To assess the absorption contribution to the value of water-leaving radiance of the sea surface layer, the data on the optical characteristics for the cases of dust transport (21.11.2021) and clear atmosphere (02.12.2021) were analyzed. The main optical and microphysical characteristics of the atmospheric aerosol during the period under study were analyzed using the data of portable solar photometers of the AERONET network. Basic information on the aerosol transfer and its type was obtained due to the data of the MODIS-Aqua, VIIRS, Sentinel and CALIPSO satellite platforms. To confirm the dust transfer from Africa, presented were the results of modeling the reverse trajectories of air flow movement performed using the HYSPLIT and AERONET software package for the Black Sea stations Section_7 (Romania), Galata_Platform (Bulgaria) and Sevastopol (Russia).
Conclusions. Study of the water-leaving radiance values based on the satellite and ground-based measurements performed at the wavelength 443 nm shows that in the presence of an absorbing aerosol, the contribution of sea brightness to the total signal becomes smaller as compared to the brightness coefficients for a background day and for a day with clear atmosphere (content of the aerosol particles is minimal). The sea water-leaving radiance constitutes 5% of the total radiance for a day with clear atmosphere, 2% – for a background day, and 1% – for a day with an absorbing aerosol in the atmosphere.

Keywords: *Sentinel*, OLCI, MODIS, VIIRS, SPM, AERONET, CALIPSO, back trajectories HYSPLIT, SILAM, Black Sea

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Introduction

Remote sensing is the main method by which a quantitative relationship between the electromagnetic spectrum obtained from satellites and *in situ* measurements is found. Quantitative results of remote sensing are based on accurate calibration of satellite sensors and atmospheric correction of the obtained data [1−3]. Atmospheric correction of satellite measurements over inland water bodies is a difficult task due to many factors (e.g., atmospheric pollution, high turbidity, floating objects, and coastal zone pixel flare effects) due to which water reflectivity value is significantly overestimated.

Information about the seawater biooptical characteristics can be obtained from an analysis of L_w (λ) radiance spectral variability of radiation emerging from the water column. The L_w (λ) value is determined from the seawater optical properties, which, in turn, depend on the quantitative and qualitative compositions of suspended and dissolved substances [4]. In order to minimize the influence of observation geometry and optical properties of the atmosphere on the value of the radiance signal, in [5] G. Gordon introduced the concept of normalized radiance L_{wn} as a characteristic of the radiation ascending from the sea surface. At the moment, the $L_{wn}(\lambda)$ value is still used as a standard product of data processing. Satellite color scanners, such as MODIS-Aqua, VIIRS, OLCI, measure the spectral radiance of the upward radiation at the upper boundary of the atmosphere (L_{TOA}), which includes radiation scattered by aerosol particles and air molecules, as well as radiation reflected by the water surface. Thus, for a correct L_w estimate, an “atmospheric correction” procedure, which excludes the contribution of these components to the L_{TOA} value, is required.

Atmospheric correction, based on the radiation transmission model, includes modeling the propagation of electromagnetic waves under conditions of variability of: 1) atmospheric parameters; 2) atmospheric regimes (associated with atmospheric gas parameters); 3) surface height and geometry of satellite observations (satellite zenith angle, sun zenith angle and relative azimuth). Using the modeling results, a lookup table of atmospheric radiation parameters with the corresponding spectral response functions of the satellite sensor is created. The method of atmospheric radiation transfer correction also includes determining the relationship between atmospheric parameters from satellite data and surface reflectivity by modeling the process of radiation transfer from a remote sensor (on the atmosphere boundary) and a sensor located directly on the underlying surface. The obtained results are applied to quantify the characteristics and parameters of the underlying surface.

Difficulties in solving problems of atmospheric correction are determined primarily by the fact that even in the open part of the World Ocean L_w (λ) in the "blue" part of the spectrum is only about 10–15% of the total radiance, where the radiation scattered by the atmosphere predominates. In coastal areas in the "blue" region of the spectrum, the L_w (λ) contribution to the radiance at the upper boundary of the atmosphere becomes less than 5% due to an increase in signal absorption by impurities contained in seawater, as well as due to an increase in the aerosol scattering variability [6].

In the presence of dust aerosol over the studied water area, atmospheric correction errors in satellite sounding become more obvious, namely, negative values of the normalized sea radiance appear [7]. The quality of satellite products is aggravated by the non-linear dependence of the scattered radiation radiance on the optical depth (molecular and aerosol components of the AOD). It should be noted that in the presence of dust aerosol in the atmosphere, the average daily AOD values increase sharply, especially in the short-wavelength region of the spectrum. Therefore, as the wavelength decreases, the number of errors increases.

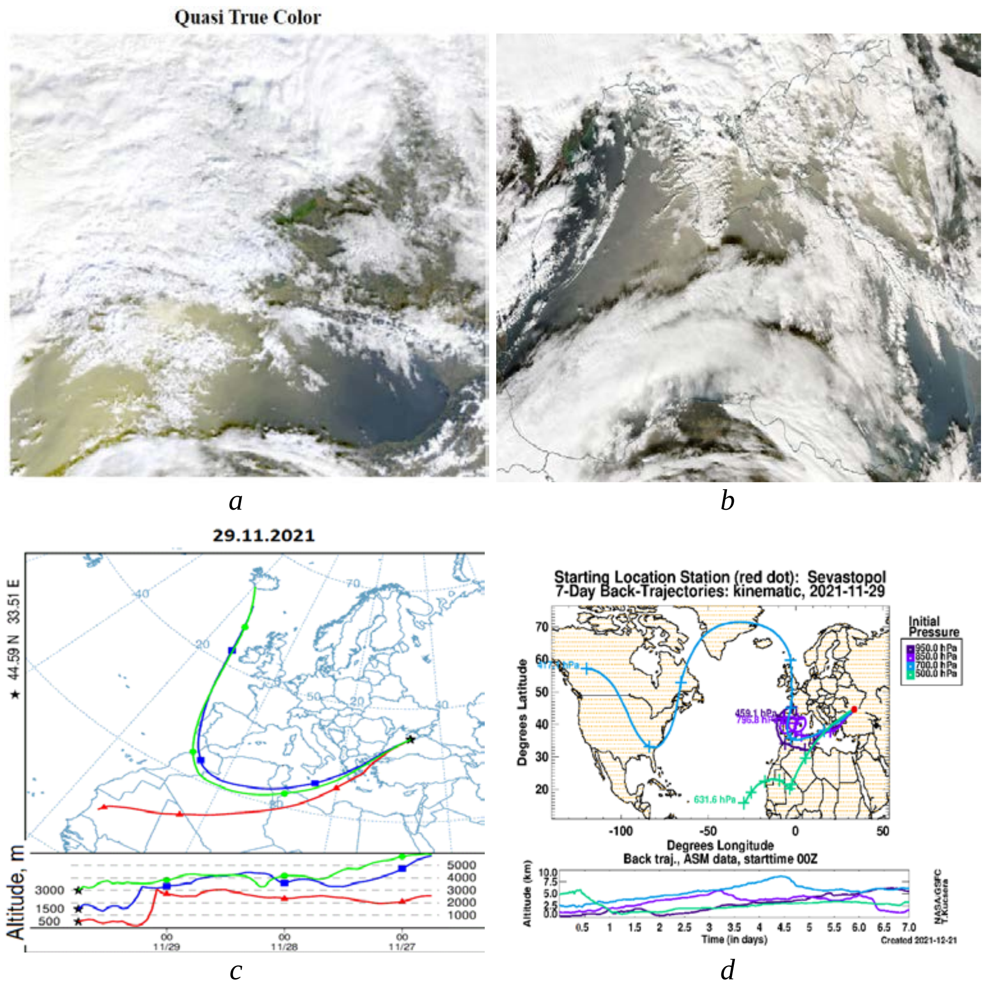
In [8] it was demonstrated that additional correction of satellite data provided by MODIS-Aqua, MODIS-Terra, taking into account dust aerosol, significantly reduces the discrepancy between *in situ* reflectivity and remote sensing data, especially in short-wavelength spectral ranges.

The purpose of this work is to carry out a comprehensive study of the case of anomalously intense precipitation in Sevastopol with a storm wind of up to 27 m/s for 29.11.2021 – 30.11.2021 period using satellite and ground-based monitoring tools to assess the effect of aerosol on optic characteristics of the sea and atmosphere for the region under study.

Instruments and materials

To analyze satellite images in 21.11.2021–02.12.2021 period for Sevastopol region, OLCI Sentinel-3b and MODIS images were analyzed (Fig. 1, *a*, *b*). For the western part of the Black Sea, for the same period only OLCI Sentinel-3b images were analyzed, since other remote sensing instruments (MODIS, VIIRS), despite the absence of clouds in this region, did not record a yellow dust plume.

The Ocean and Land Color Instrument (OLCI) is the successor to the ENVISAT Medium Resolution Imaging Spectrometer (MERIS) with additional spectral bands, different camera layouts and simplified on-board processing. OLCI is a device equipped with five camera modules that divide the field of view. The field of view of five cameras is fan-shaped in a vertical plane perpendicular to the platform speed. Each camera has an individual 14.2° field of view and 0.6° overlap with neighboring cameras. The entire field of view is offset along the track by 12.6° from the sun to minimize the effects of sun glare. OLCI is fitted with on-board equipment based on solar diffusers for calibrating the obtained measurement results. There are three solar diffusers: two "white" ones designed for radiometric calibration and one designed for spectral calibration, with spectral reflectance characteristics. The native resolution is approximately 300 m, which is called full resolution (FR). The reduced resolution (RR) processing mode provides level 1*B* data with a sampling rate reduced by a factor of four in both spatial dimensions, resulting in a resolution of ~1.2 km.



F i g. 1. Satellite image from the OLCI (a) and MODIS-Aqua (*b*) scanners; back trajectories of air masses movement based on the HYSPLIT (*c*) and AERONET (*d*) simulation data for 29.11.21 for the Sevastopol station (http://ready.arl.noaa.gov/HYSPLIT.php; https://aeronet.gsfc.nasa.gov/BAMGOMAS/index.html)

The Ocean Color algorithms for calculating the reflectivity in the upper atmosphere assume that TOA (Total Optical Aerosol) radiation is linearly divided into different physical contributions, as shown below:

$$L_{TOA}(\lambda) = [L_r(\lambda) + L_a(\lambda) + t_{dv}(\lambda)L_f(\lambda) + t_{dv}(\lambda)L_w(\lambda)]t_{gv}(\lambda)t_{gs}(\lambda)fp(\lambda), \qquad (1)$$

where $L_r(\lambda)$ is radiance contribution due to Rayleigh scattering on air molecules; $L_a(\lambda)$ is a radiance contribution due to aerosol scattering, including multiple scattering interactions with air molecules; $L_f(\lambda)$ is a seafoam contribution; $L_w(\lambda)$ is a sea radiance; $t_{dv}(\lambda)$ is a transmittance of scattered radiation through the atmosphere on the viewing path from the surface to the sensor; $t_{ds}(\lambda)$ is a transmittance of scattered radiation through the atmosphere on the viewing path from the Sun to the surface; $t_{gv}(\lambda)$ is a radiation transmittance loss due to absorbing gases for all upward radiation getting along the sensor path; $t_{gs}(\lambda)$ is a transmittance of scattered radiation through the atmosphere on the viewing path from the Sun to the surface; fp(λ) is a correction for polarization effects.

Thus, it is important to take into account the ratios of these components and their variability depending on anomalous conditions, for example, dust aerosol, when $L_a(\lambda)$ becomes many times higher, and $L_w(\lambda)$ – lower.

Since the Sentinel satellite provides data on L_{TOA} (formula (1)), the task is to normalize the values according to the formula

$$R_{\mathrm{TOA}}(\lambda) = \frac{\pi L_{\mathrm{TOA}}(\lambda)}{E_0(\lambda)\cos(\theta)},$$

where E_0 is a solar constant [9]; cos(θ) is a cosine of the zenith angle of the sun.

The reflectivity in the upper part of the atmosphere is a dimensionless quantity that determines the ratio of the reflected radiation to the solar radiation incident on a given surface. It can be calculated from satellite spectral irradiance measurements using the mean solar spectral irradiance and the solar zenith angle.

To analyze dust concentrations above the Black Sea region, the WRF (Weather and Research Forecasting) model, developed specifically for solving problems of atmospheric correction and operational forecasting, was applied. In [10], a detailed description of the WRF model is given. Along with the calculation model of weather dynamics, the WRF model can be used to estimate the presence of dust particles in the atmosphere. The physical parameters of dust detection in the WRF-Chem model are similar to the GOCART model. The WRF-Chem code is developed and maintained at NOAA/ESRL/GSD in collaboration with other research groups at NCAR (National Center for Atmospheric Research), PNNL (Pacific Northwest National Laboratory), NASA (National Academy of Science of America), ERDC (Engineer Research and Development Center) and many other institutions.

Atmospheric pollution is calculated using the SILAM (System for Integrated modeLling of Atmospheric coMposition) computer modeling system for pollutant dispersion developed by the Finnish Meteorological Institute (available at: http://silam.fmi.fi). SILAM is a modern, powerful tool for modeling the scattering properties of aerosols, gaseous constituents, dust particles, radionuclides and natural allergens in the atmosphere and is widely used to study the impact of forest fires, volcanic eruptions, dust transport, and other natural and technological disasters on atmospheric pollution in general. The scheme for calculating this effect is based on the Lagrange – Euler model. The dispersion properties of aerosol particles can vary over a wide range. SILAM allows one to model the dispersion of many chemical compounds and their mixtures with different types of interaction between them. One of the parameters that can be obtained using the SILAM is the content of suspended particles with a size of 2.5 and 10 μm (PM2.5 and PM10). Another parameter is the air quality index (denoted as AQI), which is developed by the Environmental Protection Agency. Values above 300 are "dangerous air quality", those in the range of 200–300 are "very unhealthy", 150–200 are "unhealthy", 100–150 are "bad for sensitive groups", and below 100, or rather below 50 – "air quality is good". The classification of pollution sources according to the SILAM includes identification of point and extensive sources, such as sea salt, dust, natural pollen, natural volatile organic compounds.

SILAM also provides maps of the spatial distribution of ozone at 10 m above the ground (ground level ozone). Ozone (O_3) is formed as a result of the reaction of sunlight to chemical elements and compounds that make up the air. Thus, hydrocarbons and nitrogen oxides contained in the air react with the formation of ozone directly at the source of pollution or at a distance of tens and hundreds of kilometers on the leeward side.

To obtain information about the source of smoke aerosol, we used the results of calculating the back trajectories obtained using the HYSPLIT model software package (available at: http://ready.arl.noaa.gov/HYSPLIT.php). The analysis of reverse trajectories makes it possible to track the movement of air flows at different heights and to establish the location of probable sources of impurities entering the atmosphere [11, 12].

Results

A storm wind (22–27 m/s) with anomalously intense precipitation was registered at the Sevastopol station on 29.11.2021 – 30.11.2021. On these days, the particle count of PM10 and PM2.5 was conducted by an Atmas dust meter in the atmosphere over Sevastopol, and the results of calculating the back trajectories of air mass transfer were analyzed. The trajectories were obtained using the software package of the HYSPLIT and AERONET models for the city of Sevastopol.

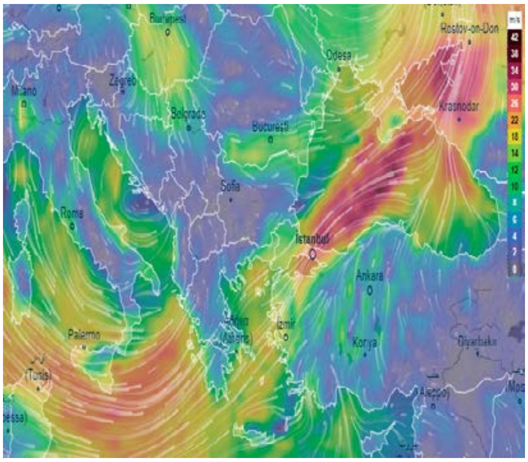
For Sevastopol, the highest concentrations for 29.11.2021 were obtained at 22:00 (PM10 = 0.07 + 0.01, which exceeds the MPC value (PM10 = 0.06 + 0), while the concentration value PM2.5 = 0.03 + 0.01). According to the data of the HYSPLIT back trajectories (Fig. 1, *c*), it can be seen that at all heights a transport from the Sahara Desert is observed. It follows from the analysis of back trajectories that for two days (29.11 and 30.11) the transfer of air masses from the African continent to any of the three (500 m, 1.5 km and 3 km) analyzed heights is recorded. At the same time, at all heights, aerosol movement is observed mainly in a southwesterly direction. This explains the brick-orange layer of pollution after rainfall on cars, windows and other surfaces that were in the open.

Similar results were also obtained by analyzing the back 7-day aerosol trajectories provided by the AERONET network (Fig. 1, *d*). Over the Black Sea region on November 29, 2021, an intense dust transport from the Sahara was registered both according to satellite and field measurements.

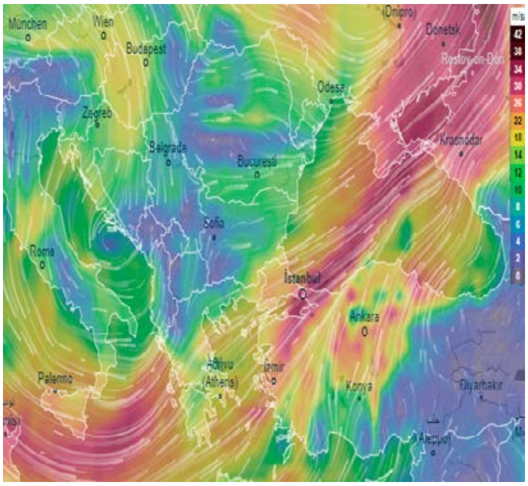
AERONET seven-day back trajectory data for 29.11.2021 also confirmed the presence of airflows from the Sahara Desert at all presented heights (500 m, 1500 m and 3 km) for the Black Sea *Section*_7 station (Romania).

Data on the wind velocity and direction according to the SILAM model at heights used to analyze the HYSPLIT and AERONET back trajectories for 29.11.2021 are shown in Fig. 2. Based on the modeling results, it can be seen that at all heights the same direction of air flows is observed, the intensity of which increases with height.

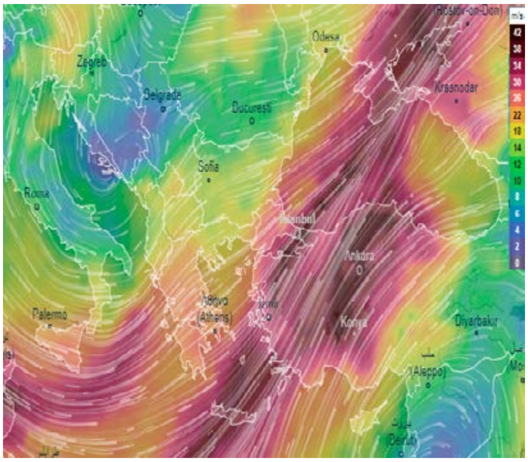
The increased (relative to the average monthly) values of the concentration of PM10, PM2.5 particles and dust particles according to the SILAM modeling data for the Sevastopol region and for the Black Sea region as a whole confirmed the dust aerosol transfer from Africa (Fig. 3). Analysis of AQI parameter and ozone content values did not show high values, which means that no threat to human health was identified during this period.



a



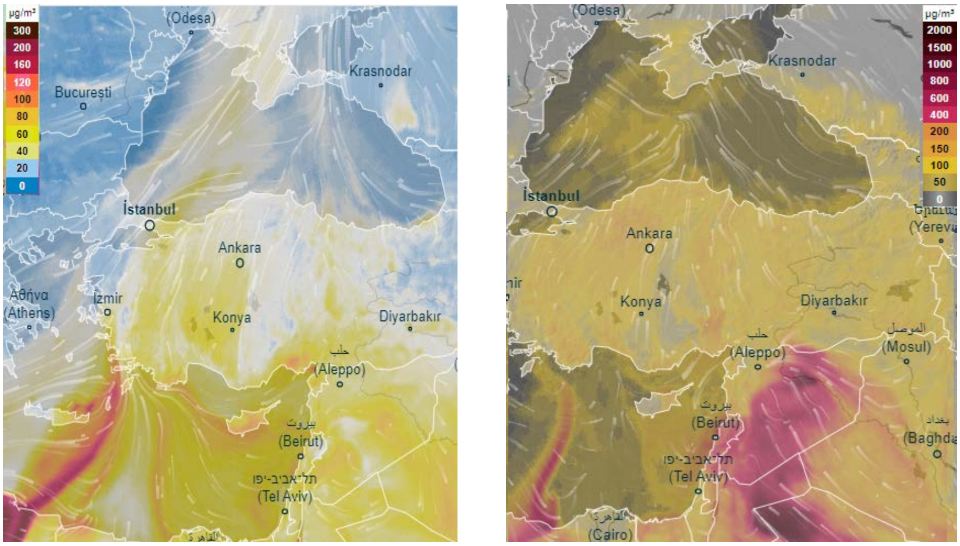
b



c

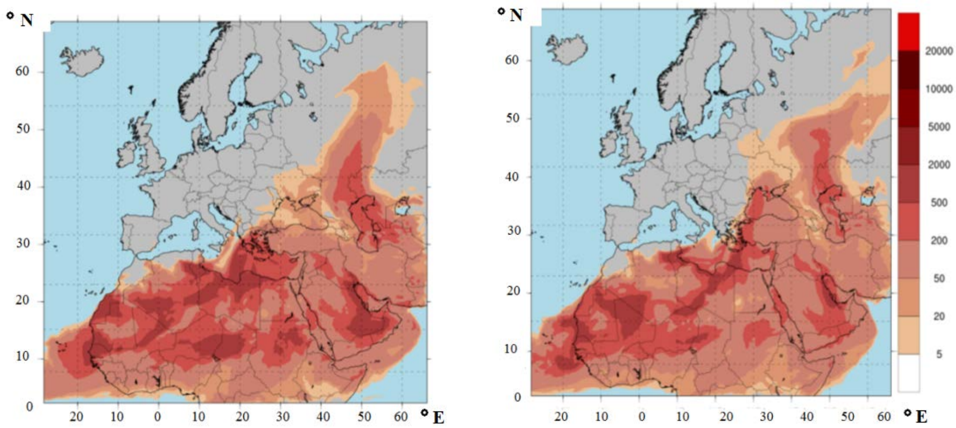
F i g. 2. Strength and direction of wind at the heights 500 m (*a*), 1.5 (*b*) and 3 km (*c*) based on to the SILAM model data for 29.11.21 (https://silam.fmi.fi)

On 29.11.2021, during the transfer of dusty air masses over Sevastopol, heavy short-term precipitation was recorded. In [13], an analysis of sediment samples for phosphorus and silicon content for the studied dates was given. As a result of the analysis, it was revealed that the concentration of silicates in atmospheric precipitation collected using an open sediment collector was more than seven times higher than the concentration of this element in 2021 according to the World Health Organization (WHO) and was 38 times higher than the WHO concentration for a closed sediment collector, which is not affected by dry precipitation [13]. Since the transport of dust aerosol on 29.11 – 30.11 was intense, a brown-orange coating, typical of dust aerosol transport from the Sahara, could be observed on all surfaces [14].



a *b*

F i g. 3. Results of simulating the concentrations of a – PM10 particles and *b* – dust in the atmosphere based on the *SILAM* data on 29.11.21, 10:00 p. m. (https://silam.fmi.fi)



a *b*

F i g. 4. Results of modeling the dust concentration variability in the atmosphere surface layer based on the WRF-Chem kinematic model data for 28.11.2021 (*a*) and 29.11.2021 (*b*) (https://ruc.noaa.gov/wrf/wrf-chem)

According to the WRF-Chem modeling data [9], on that day over Sevastopol and the western part of the Black Sea the concentration of dust particles reached 2000 μg/m^3 (Fig. 4, *b*), which is several times higher than the average monthly concentrations for the region under study. Before the dust transport in the western part of the Black Sea, the dust concentration was up to 50 μg/m^3 (Fig. 4, *a*), while after 30.11.2021, the dust plume moved to the eastern region.

This transfer was also registered from field photometric measurements at the Black Sea stations AERONET Section_7 (Romania) and Galata_Platform (Bulgaria). Section_7 station is located closer to the coast and was in the cloudy area during the study period, so the values of the aerosol optical depth (AOD) for it were expectedly higher. Thus, the average daily value of AOD at a wavelength of 500 nm (AOD(500)) for 29.11.2021 at the Galata_Platform station was 0.35 with a monthly average value of 0.09 (*level* 1.5 data), and at *Section*_7 station AOD(500) = 0.67 with an average monthly AOD(500) of 0.11. The results of estimating the contribution of coarse (τ^c) and fine (τ^f) particles to the total distribution of AOD(500) also confirmed the predominance of coarse particles in the atmosphere over both stations: the τ^c contribution is four times greater than the τ^f for the Galata_Platform station, and five times greater for Section_7 station.

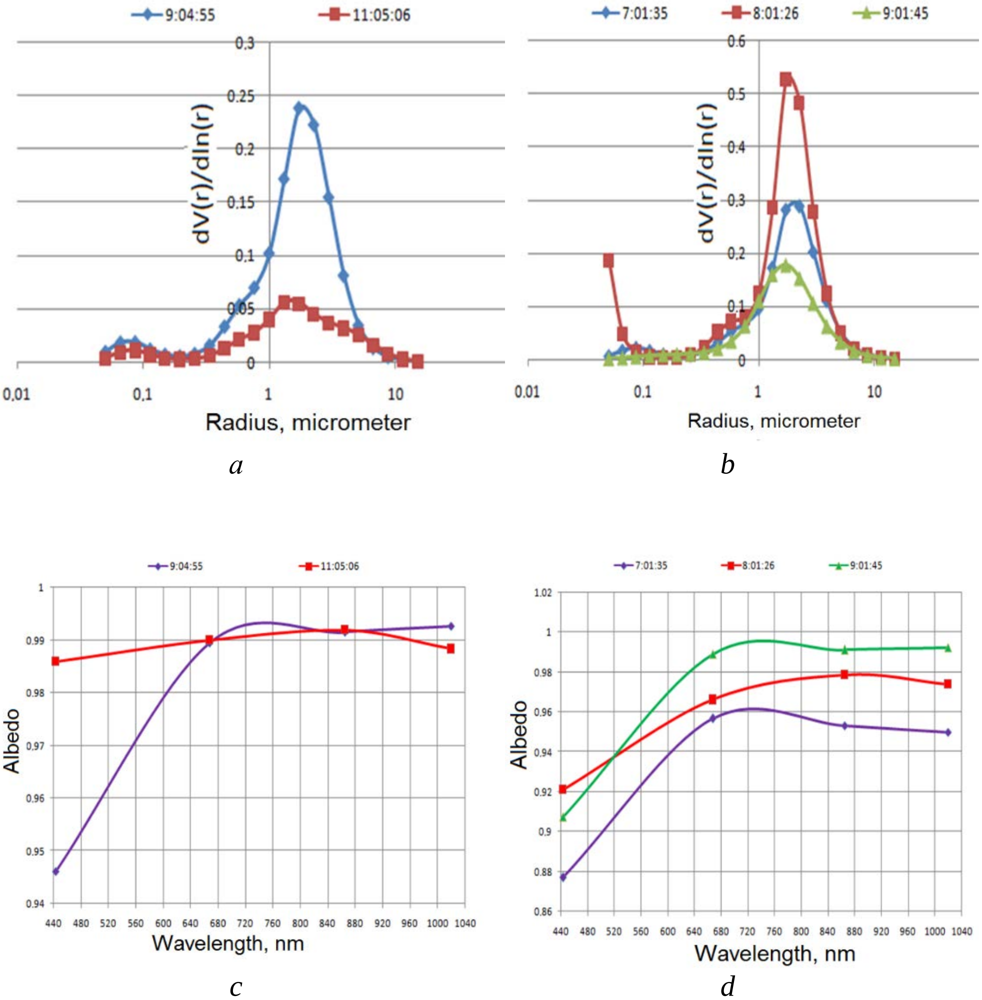
Table 1 presents the average daily measurements of AOD and the Angström parameter (α) for November 29, 2021 and the closest date with a clean atmosphere for the AERONET Galata_Platform and Section_7 stations (without clouds, haze, etc.) based on the results of processing measurements of the CIMEL photometer (level 1.5 data). Since there was continuous cloudiness over Sevastopol on 29.11.2021, the measurements with the SPM photometer are absent.

T a b l e 1

Daily average values of aerosol optical characteristics on the days with clear atmosphere (25.11.2021 and 28.11.2021) and the day of dust transfer (29.11.2021) for the Black Sea stations of the AERONET network

Parameter	Galata_Platform		Section_7	
	25.11.2021	29.11.2021	28.11.2021	29.11.2021
AOD(400)	0.099	0.367	0.183	0.684
AOD(412)	0.095	0.365	0.175	0.679
AOD(443)	0.087	0.361	0.162	0.674
AOD(490)	0.074	0.354	0.145	0.667
AOD(510)	0.069	0.353	0.140	0.665
AOD(560)	0.064	0.350	0.126	0.657
AOD(620)	0.053	0.343	0.112	0.651
AOD(667)	0.044	0.340	0.100	0.646
AOD(779)	0.034	0.334	0.082	0.636
AOD(865)	0.029	0.329	0.073	0.627
AOD(1020)	0.023	0.320	0.062	0.611
α (440-870)	1.660	0.153	1.210	0.111

According to the data from Table 1, on the day of dust transport, there is a sharp increase in AOD and a sharp decrease in α, compared to a day with a clean atmosphere, which is an indicator of the presence of absorbing aerosol in the atmosphere. Based on the data of the AERONET inversion products, the size distribution of aerosol particles for 29.11.2021 and the spectral behavior of the single scattering albedo for the Black Sea AERONET stations were analyzed (Fig. 5).



F i g. 5. Particle size distribution at stations Galata_Platform (*a*) and Section_7 (*b*); single scattering albedo at stations Galata_Platform (*c*) and Section_7 (*d*) based on the AERONET network data for 29.11.2021

Ocean Color provides level 1*B* data (calibrated radiance values), so it was decided to analyze the dust contribution to the total L_{TOA} values from Sentinel (OLCI) data, and also calculate the contribution of sea radiance $L_{wn}(\lambda)$ to the same parameter. The complexity of the analysis by remote sensing methods of optical characteristics for 29.11.2021 is due to cloudiness over the region under study on that day. The MODIS and VIIRS satellites did not record a dust plume over the Black Sea region, however, the Sentinel-3 satellite recorded the moment of formation of a dust plume (a cloud of a characteristic orange-brick color) formation, which was recorded above the western AERONET – Galata_Platform station (Table 2). The finished level 2 ocean color satellite products according to Sentinel-3 measurements for 29.11.2021 were not used, since they contained negative values of the normalized sea radiance in the short-wavelength region at a wavelength of 412 and 443 nm, which indicates atmospheric correction errors and is consistent with the works [7, 8].

Table 2

Optical characteristics of the sea derived from the satellite and ground-based measurements on 29.11.2021

Wave length, nm	Sentinel-3			AERONET		$\frac{R_{rs}}{R_{TOA}}$
	L_{TOA}, mW·cm^{-2}× ×av^{-1}·μkm^{-1}	Spectral brightness of sun, mW·cm^{-2}× ×av^{-1}·μkm^{-1}	R_{TOA}, av^{-1}	L_{wn}, mW·cm^{-2}× ×av^{-1}·μkm^{-1}	R_{rs}, av^{-1}	
400	7.491018	153.4781	0.42524	0.034	0.000695	0.001635772
412	7.916132	170.9230	0.40351	0.089	0.001635	0.004051929
443	7.809903	189.0350	0.35995	0.253	0.004202	0.011675075
490	6.689618	193.4653	0.30126	0.516	0.008374	0.027799256
510	6.071697	192.0841	0.27539	0.523	0.008549	0.031043910
560	4.705927	179.7491	0.22809	0.493	0.008610	0.003577000
620	3.768011	164.9287	0.19904	0.110	0.002090	0.010521201
779	2.444002	117.4262	0.18133	0.004	0.000100	0.000589852
865	1.862145	95.9636	0.16906	0.005	0.000160	0.000967701
1020	1.268153	69.9810	0.15788	0.009	0.000400	0.002557735

Note. On 29.11.2021, the sun zenith angle was 68.87396°(cos(68.8739°) = 0.3604).

The AERONET data on $L_{wn}(\lambda)$ were also normalized to the solar constant. Then, the absorption contribution to the value of the sea surface layer radiance was estimated for the day of dust transport and for the day with a clean atmosphere (21.11.2021 and 02.12.2021) (Table 3). During the study, the SeaDAS software package, which processed satellite images while maintaining high data quality (the selected pixels corresponding to the coordinates of Galata_Platform station do not have error flags), was applied.

Comparing the results of Table 2 and 3, it can be seen that the L_{wn} maximum contribution to the total radiance distribution is in the visible range at a wavelength of 560 nm. For a day with a clean atmosphere (02.12.2021), the L_{wn} maximum contribution is 17%. For the background day (21.11.2021), with a slight haze in the images and higher AOD values according to satellite data than for 02.12.2021, the sea radiance contribution is 9%. During the dust transfer over the Black Sea region on 29.11.2021, due to cloudy atmosphere, the sea is almost invisible, and its contribution is 3.7%, which is 4.5 times less than on 02.12.2021.

Table 3

Optical characteristics of the sea derived from the satellite and ground-based measurements on 21.11.2021 and 02.12.2021

Wave length, nm	Sentinel-3			AERONET		$\frac{R_{rs}}{R_{TOA}}$
	L_{TOA}, mW·cm^{-2}× ×av^{-1}·μkm^{-1}	Spectral brightness of sun, mW·cm^{-2}× ×av^{-1}·μkm^{-1}	R_{TOA}, av^{-1}	L_{wn}, mW·cm^{-2}× ×av^{-1}·μkm^{-1}	R_{rs}, av^{-1}	
21.11.2021						
400	6.566571	153.4781	0.357681	0.161	0.0032939	0.009209
412	6.795762	170.9230	0.332385	0.238	0.0043723	0.013154
443	6.119268	189.0350	0.270621	0.397	0.0065944	0.024368
490	4.592702	193.4653	0.198458	0.634	0.0102900	0.051850
510	3.929536	192.0841	0.171023	0.646	0.0105602	0.061747
560	2.535659	179.7491	0.117931	0.617	0.0107782	0.091394
620	1.477196	164.9287	0.074877	0.153	0.0029129	0.038903
779	0.561470	117.4262	0.039973	0.005	0.0001337	0.003345
865	0.331855	95.9636	0.028910	0	0	0
1020	0.143767	69.981	0.017174	-0.003	-0.0001346	-0.00784
02.12.2021						
400	4.901749	153.4781	0.278878	0.196	0.00400995	0.014379
412	4.980188	170.923	0.254422	0.313	0.00575007	0.022601
443	4.461363	189.035	0.20608	0.571	0.00948470	0.046024
490	3.304922	193.4653	0.149165	1.052	0.01707428	0.114465
510	2.788113	192.0841	0.126744	1.014	0.01657586	0.130782
560	1.773757	179.7491	0.086166	0.870	0.01519785	0.176378
620	1.079895	164.9287	0.057174	0.184	0.00350309	0.061271
779	0.372644	117.4262	0.027710	0.005	0.00013370	0.004825
865	0.213768	95.9636	0.019451	0	0	0
1020	0.102138	69.981	0.012744	-0.001	-0.00004500	-0.003520

N o t e. On 21.11.2021, the sun zenith angle was 67.9379° (cos(67.9379°) = 0.3756), on 02.12.2021 – 68.92097° (cos(68.92097°) = 0.3596).

According to the SPM data obtained in Sevastopol, the following dates were analyzed in a similar way: 1) 21.11.2021 – a background day with a moderately turbid atmosphere, when the AOD values were close to the monthly average values (AOD(500) = 0.086 with the monthly average AOD(500) = 0.098); and 2) 02.12.2021– with a clean atmosphere, for which AOD(500) = 0.042, which is three times less than the average monthly value of AOD(500) (0.127). For the same dates, the AOD values were analyzed according to the data of photometric measurements within the framework of the AERONET network operation for Galata_Platform station. As well as for Sevastopol, the data obtained by the CIMEL photometer for the western coast of the Black Sea revealed the values close to the monthly average ones for 21.11.2021 and two times less than the average monthly AOD data for 02.12.2021.

It should be noted that the measurement results of other satellite sensing instruments were not used in this work.

Conclusion

The study presents the results of the analysis of normalized sea radiance natural values, obtained at the coastal stations of the northwestern part of the Black Sea, namely Galata_Platform and Section_7, as well as the results of measurements and modeling of the water-leaving radiance for Sevastopol. The percentage contribution of $L_{wn}(\lambda)$ value to the total water-leaving radiance value was calculated for three cases: under the conditions of clean atmosphere, presence of a weakly absorbing background aerosol, and at the transfer of the absorbing dust aerosol. To exclude the impact of phytoplankton blooms, three dates were selected in the autumn period for the analysis of radiance coefficients, for which satellite images (Level 1) were analyzed in the *SeaDas* software package.

A comparative analysis of field and satellite data showed that the $L_{wn}(\lambda)$ maximum contribution to the total radiance distribution is in the visible range at a wavelength of 560 nm. For a date with a clean atmosphere (02.12.2021), the $L_{wn}(\lambda)$ maximum contribution is 17%. For a background day (21.11.2021), with a slight haze in the images and higher satellite AOD values than on 02.12.2021, the brightness contribution is 9%.

During the dust transfer over the Black Sea region (29.11.2021), due to the cloudy atmosphere and high absorption by coarse particles, the sea is almost invisible and its contribution is 3.7%, which is 4.5 times less than on 02.12.2021. The smaller the contribution of sea radiance to the total radiance, the greater the probability of atmospheric correction errors.

The cases of dust transfers are characterized by the fact that the average height of absorbing particles is noticeably higher than that of industrial and continental type aerosols. Above the surface, the aerosol is stratified in accordance with the intensity of turbulent exchange, which, as a rule, is much greater over land. Accordingly, when the dust aerosol is transferred towards the sea, the continental aerosol is located above the oceanic aerosol.

This study shows that at a wavelength of 443 nm, the percentage ratio of sea radiance to the total radiance $\frac{R_{\text{rs}}}{R_{\text{TOA}}}$ on a day with a clear atmosphere is 5%, on a background day it is 2%, and in the presence of absorbing aerosol, the contribution of sea radiance becomes even smaller, and exactly 1%. Therefore, the development of an atmospheric correction algorithm for coastal waters, for which dust transfer events are recorded year-round, is an urgent task. The results of reconstructing sea radiance values under such conditions using existing algorithms are highly likely to be unreliable.

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