ISSN 2413-5577, Ecological Safety of Coastal and Shelf Zones of Sea, 2025, No. 3, pp. 141–162.

Original paper

Optical Characteristics of Atmospheric Aerosol over the Black Sea and Reservoirs of the Middle and Lower Volga for 2022–2024

D. V. Kalinskaya [1, 2] *, **A. A. Molkov** [1, 3]

[1] *Lobachevsky Nizhny Novgorod State University, Nizhny Novgorod, Russia*
[2] *Marine Hydrophysical Institute of RAS, Sevastopol, Russia*
[3] *A.V. Gaponov-Grekhov Institute of Applied Physics of RAS, Nizhny Novgorod, Russia*
* *e-mail: kalinskaya_d_v@mail.ru*

Abstract
The paper presents the results of a comprehensive analysis of atmospheric aerosol based on *in situ* photometer SPM measurements data, MODIS (Aqua/Terra) and VIIRS satellite data, and HYSPLIT air flow modeling data. The study was conducted by comparing the optical characteristics obtained during the same periods over the Black Sea region and tracking the movement of aerosol towards reservoirs located in different parts of the Volga River: the Middle Volga (Gorky and Cheboksary Reservoirs) and the Lower Volga (Kuybyshev and Volgograd Reservoirs). The analysis revealed the days of dust aerosol presence in the atmosphere. We compared the periods when high values of the aerosol optical depth (AOD) and low values of the Angstrom exponent were obtained for the Black Sea and for the Volga River. The periods when high values of AOD and low values of the Angstrom exponent were obtained simultaneously for the Black Sea and for the Volga River region were identified. A key finding of this study is the stability of the aerosol optical characteristics over the Black Sea and the Kuybyshev Reservoir, which persisted even during intensive dust transport from the Sahara Desert. This proves that regional algorithms for the Black Sea can be used to restore the brightness coefficients from satellite data when there is dust aerosol in the atmosphere over the Volga River reservoirs. The presented results provide a preliminary description of the atmosphere optical characteristics in the study regions and may be useful for testing the accuracy of standard atmospheric correction algorithms for satellite data.

Keywords: SPM, MODIS, VIIRS, SILAM, backward trajectories of HYSPLIT, Angstrom exponent, dust aerosol, smoke aerosol, aerosol optical depth, AOD, Volga, Black Sea, atmospheric aerosol

Acknowledgements: The work was carried out at the expense of the RNF grant No. 23-17-00071 (“Volga bio-optical algorithms”), https://rscf.ru/project/23-17-00071. The authors express their gratitude to S. M. Sakerin and D. M. Kabanov for providing the SPM photometer and its software and for the possibility of using high-quality photometric measurement data. The authors also thank Air Resources Laboratory (ARL) and the developers of HYSPLIT for providing high-quality simulation data in a timely manner. The authors express their gratitude to Kapustin I.A. and Leshchev G.V. for their participation in performing *in situ* measurements. For the Black Sea the researches were performed under state assignment of the Marine Hydrophysical Institute of the Russian Academy of Sciences FNNN-2024-0012 “Analysis, diagnosis and operational forecast of the state of hydrophysical and hydrochemical fields of marine waters based on mathematical modeling using data from remote and contact measurement methods” (“Operational Oceanology”).

For citation: Kalinskaya, D.V. and Molkov, A.A., 2025. Optical Characteristics of Atmospheric Aerosol over Reservoirs of the Middle and Lower Volga in Comparison with the Black Sea for the Period 2022–2024. *Ecological Safety of Coastal and Shelf Zones of Sea*, (3), pp. 141–162.

Оптические характеристики атмосферного аэрозоля над Черным морем и водохранилищами Средней и Нижней Волги за 2022−2024 годы

Д. В. Калинская [1, 2] *, А. А. Мольков [1, 3]

[1] *Нижегородский государственный университет им. Н. И. Лобачевского, Нижний Новгород, Россия*
[2] *Морской гидрофизический институт РАН, Севастополь, Россия*
[3] *Институт прикладной физики им. А. В. Гапонова-Грехова РАН, Нижний Новгород, Россия*
* *e-mail: kalinskaya_d_v@mail.ru*

Аннотация
Представлены результаты комплексного анализа атмосферного аэрозоля с использованием натурных фотометрических измерений *SPM*, спутниковых данных *MODIS* (*Aqua*/*Terra*), *VIIRS*, а также моделирования траекторий перемещения воздушных потоков *HYSPLIT*, проведенного в рамках сопоставления оптических характеристик атмосферного аэрозоля над регионом Черного моря и водохранилищами бассейна р. Волги (Горьковским, Чебоксарским, Куйбышевским и Волгоградским). Анализ основан на данных, полученных в одни и те же периоды, с последующим отслеживанием перемещения аэрозоля в направлении волжских водохранилищ. В ходе работы выявлены дни с присутствием в атмосфере пылевого аэрозоля. Проведено сравнение периодов, в которые были получены высокие значения аэрозольной оптической толщины и низкие − параметра Ангстрема над Черным морем и Волгой. Выявлены периоды, когда данные аномалии наблюдались синхронно в обоих регионах. Ключевой результат данного исследования состоит в том, что оптические характеристики аэрозоля над Черным морем и Куйбышевским водохранилищем в период интенсивного пылевого переноса со стороны пустыни Сахары не претерпели значимых изменений. Это свидетельствует о возможности применения региональных алгоритмов, разработанных для Черного моря, при восстановлении коэффициентов яркости по спутниковым данным над водоемами р. Волги в условиях присутствия в атмосфере пылевого аэрозоля. Представленные результаты формируют предварительное описание оптических характеристик атмосферы в исследуемых регионах и могут быть использованы для оценки точности стандартных алгоритмов атмосферной коррекции спутниковых данных.

Ключевые слова: *SPM, MODIS, VIIRS, SILAM*, обратные траектории *HYSPLIT*, параметр Ангстрема, пылевой аэрозоль, дымовой аэрозоль, аэрозольная оптическая толщина, АОТ, Волга, Черное море, атмосферный аэрозоль

Благодарности: работа выполнена за счет гранта РНФ № 23-17-00071 («Волжские биооптические алгоритмы»), https://rscf.ru/project/23-17-00071. Авторы выражают признательность С. М. Сакерину и Д. М. Кабанову за предоставление фотометра *SPM* и программное обеспечение к нему и за возможность использования качественных данных фотометрических измерений. Также авторы благодарят *Air Resources Laboratory's* (*ARL*) и разработчиков *HYSPLIT* за своевременное предоставление качественных данных моделирования. Авторы выражают благодарность И. А. Капустину и Г. В. Лещеву за участие в выполнении натурных измерений. Исследования над Черным морем выполнены в рамках темы государственного задания Морского гидрофизического института РАН FNNN-2024-0012 «Анализ, диагноз и оперативный прогноз состояния гидрофизических и гидрохимических полей морских акваторий на основе математического моделирования с использованием данных дистанционных и контактных методов измерений («Оперативная океанология»)».

Для цитирования: *Калинская Д. В., Мольков А. А.* Оптические характеристики атмосферного аэрозоля над Черным морем и водохранилищами Средней и Нижней Волги за 2022−2024 годы // Экологическая безопасность прибрежной и шельфовой зон моря. 2025. № 3. С. 141–162. EDN AIMHIF.

Introduction

The primary objective of satellite oceanography is to obtain reliable information about the state of various water bodies and to study trends in changes in their water quality as well as to assess the impact of anthropogenic and biogenic factors on water areas. A variety of natural phenomena, including forest fires, dust storms and volcanic eruptions, as well as a range of technological processes, result in an increase in the amount of harmful substances entering the atmosphere and hydrosphere [1–3]. When solid fuels are burned, toxic chemicals are released into the environment as part of the exhaust gases. The most prevalent of these are carbon monoxide, sulfur dioxide, nitrogen oxides, hydrocarbons and dust [4–6].

The growing pollution of air basins in several cities demonstrates the substantial impact of modern industrial production on the natural environment, disrupting the existing balance and cycle of substances and energy. Therefore, long-term programs to maintain the normal functioning of natural ecological systems are becoming increasingly important [2−6].

The objects of study are the Black Sea (western and Crimean coasts, where the AERONET (AErosol RObotic NETwork) Galata_Platform (43.0° N, 28.2° E) and Sevastopol (44.58° N, 33.43° E)) and the Volga River reservoirs. The first measurements of atmospheric characteristics over the Black Sea were made as early as 1910, and systematic photometric observations within the framework of the international AERONET program have been conducted since 2006. In 2015, the second stage of photometric measurements was initiated using the domestic SPM (Sun Photometer Mobile) photometer analogous to the AERONET instruments.

Unlike the Black Sea, comprehensive studies of the Volga as a single ecological system have not yet been conducted. Effective river monitoring requires analysis of the entire water system, including three interrelated components: the atmosphere, the aquatic environment and the aquatic organisms. The water body ecological and toxicological state is determined by interdependent processes such as water exchange with the atmosphere, transport of toxic substances through the air and entry of pollutants into the water [7]. Therefore, a comparison of data from these two regions enables the identification of both general patterns of aerosol transport and transformation, and processes that are specific to each region.

In 1995−2003, a large amount of data on gas emissions into the atmosphere was obtained in the Volga River basin. Analysis of this data revealed a trend toward improvement in atmospheric conditions: total gas emissions into the atmosphere over the Volga basin decreased by 2.0 million tons, from 9.1 million tons in 1995 to 7.1 million tons in 2003. In 2017−2019, as part of the federal project "Revitalization of the Volga," a concept was developed to reduce diffuse pollution of the Volga [8], based on an analysis of hydrological data on pollutants and atmospheric parameters.

Nevertheless, the current data are insufficient to solve a significant applied problem, namely the use of optical satellite information to assess the quality of the Volga River waters. Furthermore, the role of long-range intensive aerosol transport, particularly the influence of intensive air flow from the Black Sea region on atmospheric characteristics over the Volga basin, remains under-researched. In order to resolve these issues, a thorough investigation is necessary that incorporates data regarding the state of the atmosphere and the aquatic environment.

In this regard, the present study focuses on comparing the optical characteristics of atmospheric aerosols over the Black Sea and the Volga reservoirs, which allows for the identification of general patterns of aerosol particle transport and transformation in both regions.

The analysis employed *in situ* data, MODIS (Aqua/Terra) satellite data, Visible Infrared Imaging Radiometer Suite (VIIRS) data and the results of air flow modeling using the HYSPLIT model for four reservoirs located in different parts of the Volga River: the Middle Volga (Gorky and Cheboksary Reservoirs) and the Lower Volga (Kuybyshev and Volgograd Reservoirs) (Fig. 1), in comparison with similar data obtained over the Black Sea.

For each of the regions studied, background characteristics of atmospheric aerosols were determined, serving as a reference point for assessing the consequences of aerosol impact. Background characteristics in this work refer to the average values of optical parameters calculated with the exclusion of emissions. The background aerosol in the regions under study consists primarily of submicron fractions of mineral dust and other aerosols (predominantly sulphate) of continental origin. These particles have penetrated through the cloud filter into the upper troposphere at an altitude of 2–3 km over the oceans and 5 km over the continents and have been distributed there relatively evenly, with a particle number concentration of ~ 300 cm^{-3} at standard temperature and pressure [9].

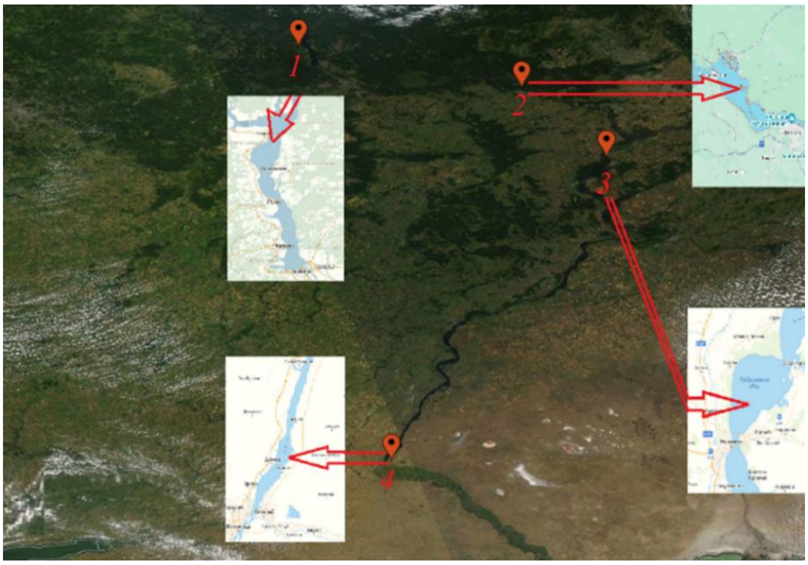
To compare, Table 1 demonstrates such background characteristics of atmospheric aerosol as aerosol optical depth (AOD) at a wavelength of 500 nm (AOD(500)) and Angstrom exponent (α) in different regions. For instance, in the Northern Tian Shan region, which is affected by dust aerosols, the AOD(500) value during the period of aerosol transport to the region was found to be 0.74 ± 0.14, which exceeds the background values (Table 1) by more than three times [10]. In the Baikal region, which is mainly affected by seasonal fires, the AOD values exceed background levels by six to eight times across most of the spectrum when smoke is present in the atmosphere [11]. The background values for the region of Middle Urals, which is subject to dust emissions and smoke transport from fires, are presented based on the results of optical characteristic measurements conducted at the Kourovka Astronomical Observatory (Sverdlovsk Oblast) and in Ekaterinburg [12]. The estimation of background values of atmospheric aerosol for central Russia can be made based on the variability of optical characteristics obtained in Moscow and the Moscow region. Thus, background values for this region, according to data from the Zvenigorod Scientific Station of A. M. Obukhov Institute of Atmospheric Physics RAS, are given in [13]. For the Siberian region, background values for atmospheric aerosols were obtained from photometric measurements at the Fonovaya station, Tomsk Oblast. During periods of intense fire in this region, the AOD(500) index has been recorded at 0.95 ± 0.86, which is approximately six times higher than background values and 2.5 times higher than the typical values for smoke aerosols [14]. The establishment of background levels is a prerequisite for the subsequent identification of anomalies caused by long-range transport of aerosols.

Table 1. Background optical characteristics of atmospheric aerosol obtained over various regions

Region/city	Background AOD(500)	Angstrom exponent α
Northern Tian Shan	0.24 ± 0.09	–
Baikal region	< 0.1	–
Sverdlovsk Oblast	0.135 ± 0.128	–
Ekaterinburg	0.168 ± 0.126	1.239 ± 0.3
Zvenigorod	0.17 ± 0.06	1.46 ± 0.4
Tomsk Oblast	0.16 ± 0.08	1.4 ± 0.4

In particular, periods were selected for analysis when the values of AOD and the Angstrom exponent deviated significantly from background levels. This facilitated the identification of episodes of intensive air flow from the Black Sea region towards the Volga basin, and the subsequent quantitative assessment of their impact on the optical properties of the atmosphere over reservoirs.

Ground-based photometric measurements were used to verify satellite data and modeling results. Ground-based solar photometry is one of the main remote sensing methods for determining the composition of atmospheric gases and aerosols, along with satellite remote sensing. The primary benefit of satellite systems is their extensive coverage capacity, which facilitates the description of the spatial distribution of the optical characteristics of the atmosphere (e.g., MODIS radiometers on the Terra and Aqua satellites). However, the underlying surface reflectivity is unpredictable enough, which significantly limits the AOD determination accuracy, allowing reliable data to be obtained only in a narrow spectral range. This creates serious difficulties in determining the composition of aerosol particles. The advent of remote sensing methods has contributed to the emergence of innovative ship- and satellite-based technologies and systems, facilitating the operational monitoring of water quality in such eutrophic water bodies as the Gorky, Kuybyshev and Volgograd Reservoirs. In light of the constraints imposed by remote methods, *in situ* studies of aerosols employing photometers continue to be a pertinent undertaking. The factors influencing the composition of aerosols, including meteorological conditions, are not yet fully elucidated.



F i g . 1 . Location of the study geographical objects on the Volga River. The numbers denote reservoirs: *1* – Gorky Reservoir; *2* – Cheboksary Reservoir; *3* – Kuybyshev Reservoir; *4* – Volgograd Reservoir (Satellite VIIRS)

This study aims at a comprehensive analysis of the optical characteristics of atmospheric aerosols over the Black Sea and four reservoirs in the Volga River basin (Gorky and Cheboksary in the Middle Volga, Kuybyshev and Volgograd in the Lower Volga) in 2022–2024 based on *in situ* measurements, satellite observations (MODIS/Aqua-Terra, VIIRS) and HYSPLIT air flow trajectory modeling data. The research objectives include comparing the spatio-temporal variability of aerosol parameters over the specified regions, tracking the transport of aerosol masses from the Black Sea towards the Volga reservoirs, and analyzing the characteristics of their distribution over these water areas.

Instruments and materials

The AOD was determined using *in situ* measurements obtained from two types of solar photometer: the AERONET reference instrument Cimel [15] and its domestic counterpart SPM (Sun Photometer Mobile) [16]. Both instruments operate in the wavelength range of 340–2134 nm. When operating and calibration conditions are met, the error in determining AOD is 0.01–0.02 and in determining the atmosphere moisture content is approximately 0.1 g/cm². A detailed description of the calibration and calculation methods for the desired characteristics is provided in [16–18].

Satellite data on AOD and Angstrom exponent were obtained using the MAIAC (Multi-Angle Implementation of Atmospheric Correction) algorithm based on MODIS/Terra and MODIS/Aqua data [19, 20]. The spatial resolution of the algorithm is 1 km, which facilitates the tracking of small-scale urban pollution, smoke from fires (including small local outbreaks), and dust storms. The selection of this product was determined by its accessibility, high resolution, and capacity to monitor aerosol dynamics in near real time.

In order to analyze the sources of aerosol transport in the Black Sea region as well as the Gorky, Kuybyshev and Volgograd Reservoirs, the results of modeling the backward trajectories of air flow movements were used. This modeling was carried out using the HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory model developed by Air Resources Laboratory (ARL)) software package [1)]. The simulation results demonstrate the predominance of western air mass transport in the region under study [1)]. This study presents the first analysis of not only backward but also forward trajectories of air currents over the Black Sea. This made it possible to compare optical characteristics with the time shift of aerosol movement over the Black Sea and, several days later, over the reservoirs.

The VIIRS radiometer set provides users with Deep Blue NASA Standard Level-2 (L2) aerosol products from the Joint Polar Satellite System (JPSS). Since 17 February 2018, the VIIRS Deep Blue Aerosol (DBA) algorithm has been used

[1)] Available at: http://ready.arl.noaa.gov/HYSPLIT.php [Accessed: 25.08.2025].

to obtain AOD values [21, 22]. The Deep Blue algorithm is used to analyze data obtained over land, while the Satellite Ocean Aerosol Retrieval (SOAR) algorithm is used over water areas. Data obtained in certain VIIRS operating ranges and processed using two algorithms described above provide ultimately reference AOD L2 Deep Blue values at a wavelength of 550 nm for the region under study [22, 23].

The Dark Target/Bright Target Algorithm (DBA) was applied to VIIRS data to create a long-term climate data series on atmospheric aerosols. The DBA algorithm was originally developed to detect aerosols over bright surfaces. To achieve this objective, a global database of surface reflectivity coefficients with a resolution of 0.1° in the visible spectrum was created using the method described in [24]. The aerosol type and AOD are determined simultaneously using look-up tables based on satellite observations. The MODIS Collection 6 (C6) data are reprocessed using an algorithm that employs three different approaches to determine surface reflectivity coefficients in different terrain types (arid/semi-arid regions, vegetated, urban/built-up and transitional areas). To identify smoke aerosols, the spectral curvature method is used, based on the ratio of surface reflectivity coefficients at wavelengths of 412/488 and 488/670 nm. In addition to VIIRS data, new models of non-spherical dust particles are also used to improve the accuracy of AOD determination. In 2020, the latest V011 DB L2 aerosol products were integrated into the data processing system. The methodology permits the extension of the range of detectable surfaces from the brightest to the very darkest [24, 25], improving aerosol monitoring capabilities significantly.

One of the tasks of the DBA and SOAR algorithms is to determine the types of atmospheric aerosols during the daytime in the absence of clouds and snow. Over land, the aerosol type is classified based on the AOD values, Angstrom exponent (α), Lambert-equivalent reflectivity (LER) and brightness temperature. The combined aerosol type over land and ocean is determined based on pixels that have passed quality control [21, 22, 24].

CALIPSO satellite data were analyzed to determine the predominant aerosol type. The main objective of CALIPSO is to measure the characteristics of aerosols and clouds on a global scale. The CALIPSO algorithm classifies aerosols by type based on the measured depolarization coefficient (δv): pure marine aerosol ($\delta v \in [0.025–0.05]$), particles of polluted dust or smog ($\delta v \in [0.05–0.15]$), most likely dust aerosol ($\delta v \in [0.15–0.5]$). The spatial resolution for most types of aerosols is 80 km, with the exception of clean marine and polluted continental aerosols. About 80% of smog and 60% of polluted dust aerosols are found over the water surface. Clean dust is distributed approximately evenly over both land and water surfaces [25, 26].

Measurements of the optical characteristics of the atmosphere over the Black Sea and the Volga River were carried out from small vessels or from the shore. The periods of atmospheric aerosol measurements over the reservoirs of the Volga River are shown in Table 2. Measurements over the Black Sea were carried out simultaneously.

T a b l e 2. Qualitative and quantitative data on measurements of main atmosphere optical characteristics over reservoirs of the Volga River

Reservoir	Period	Number of measurements
Gorky Reservoir	Spring−summer 2022−2024	292
Cheboksary Reservoir	09.09.2023−10.09.2023; 16.09.2023−17.09.2023	18
Kuybyshev Reservoir	17.07.2023−28.07.2023; 09.09.2023−16.09.2023	58
Volgograd Reservoir	28.05.2024−07.06.2024	13

As Table 2 shows, in the case of the Gorky Reservoir, the focus is on seasonal trends rather than specific periods. This discrepancy can be attributed to the fact that while expeditions in the region of the reservoir were ongoing, the measurements were taken over the course of a single day, a week or more.

During expeditions to study the optical properties of the atmosphere over the Middle and Lower Volga region, data were obtained on the AOD variability across the entire operating range of the SPM photometer, namely at 11 wavelengths: 340, 379, 441, 501, 548, 675, 872, 940, 1244, 1020 and 1556 nm. The most interesting channels for research are those close to satellite channels: comparative analysis of remote and *in situ* data makes it possible to solve many problems in both optics and hydrophysics in general. For central Russia, the AOD values above 0.3 at a wavelength of 500 nm are considered to be high. The present study determines the type of aerosol and the region that was the source of aerosol activity for dates with such values.

Results

As previously mentioned, 2015 marked the start of a period in which the optical properties of atmospheric aerosols over the Black Sea were monitored using an SPM photometer. This enabled a new stage of comparative studies of different regions equipped with similar instruments to begin. The nearest water body where photometric measurements are carried out is the Volga River basin. This paper presents a comparative analysis of the optical characteristics of atmospheric aerosols obtained over the Black Sea (in the western and Crimean coastal zones), alongside data from regular measurements taken over the Gorky, Cheboksary, Kuybyshev and Volgograd Reservoirs, as well as in the Nizhny Novgorod Oblast, between April 2022 and July 2024. The activity of dust and smoke aerosol transport from forest fires was also studied during this period.

Analysis of seasonal AOD trends in many regions of central and southern Russia revealed a primary maximum in spring and a secondary maximum in summer, the latter of which is more pronounced during intense forest fires. As is well known, a large number of forest fires are recorded in both the Black Sea region and the Nizhny Novgorod Oblast during the summer period. These fires can cause cloudiness in the atmosphere and, accordingly, lead to an increase in the values of the main optical characteristics of atmospheric aerosols during this period [25]. It is known that dust and smoke aerosols are characterised by AOD values that are more than twice the monthly average [1−3]. Fig. 2 shows average daily values of AOD(500) for the period of synchronous atmospheric studies over the Black Sea (Crimean coast (Fig. 2, *a*) and western coast of the Black Sea (Fig. 2, *b*)) and the Volga River basin (Fig. 2, *c*). As can be seen, high AOD(500) values were recorded over the Volga River in April, July and August 2022 as well as in April 2023. To determine the main source of aerosol input that has the greatest impact on the properties of the underlying surface as determined by remote sensing methods, it is necessary to analyze the seasonal and daily variability of aerosol optical characteristics.

Fig. 2, *b* shows that the maximum AOD values were observed on 13 April, 6, 7, 24–27 July, 5–8, 24–27 August in 2022; on 12, 24–28 April, 25–27 May, 18, 26–28 July in 2023; and on 4 June 2024. In general, increases in AOD values are not short-term events occurring over the course of a single day, but rather periodic in nature. This can be the result of intense dust transport and large-scale forest fires, the latter of which are a source of burning biomass aerosols (smoke aerosols). The only exception is a slight increase in AOD in the summer of 2024. However, it should be noted that measurements only began at the end of May in 2024.

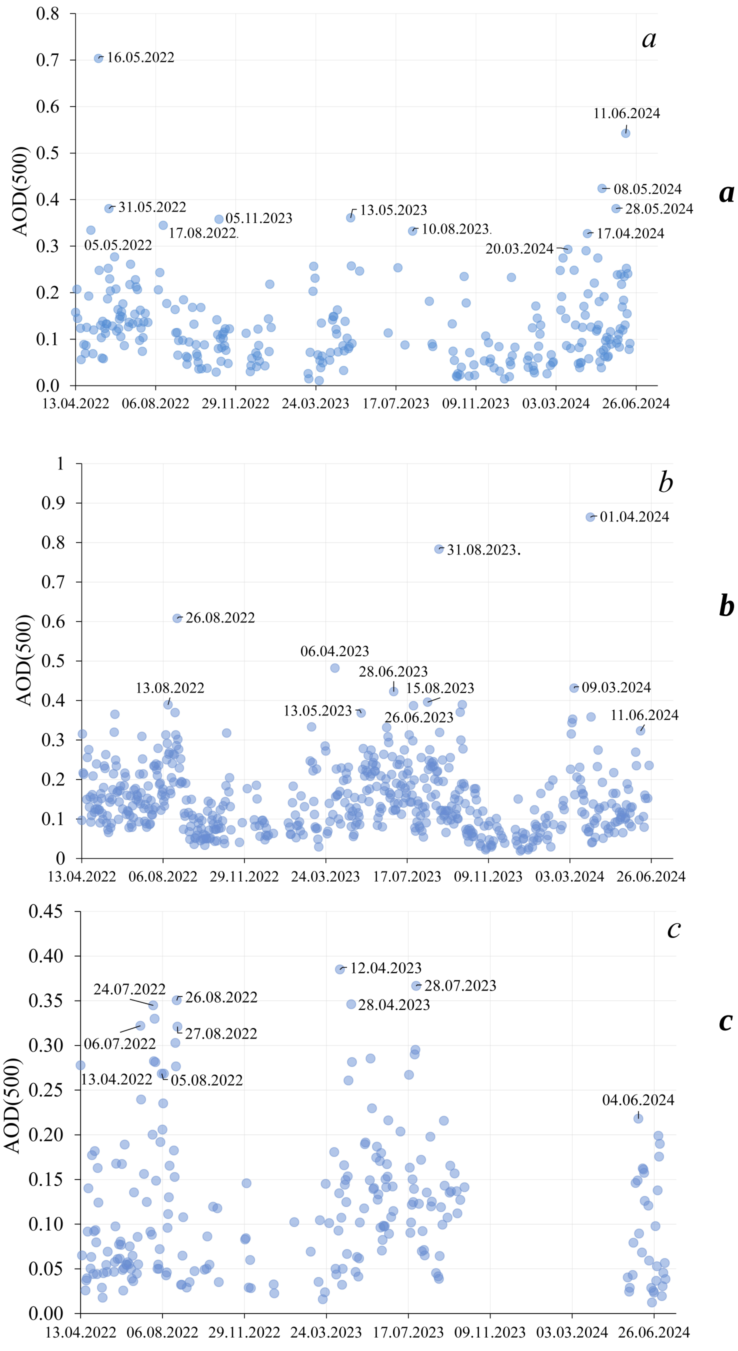
Gorky Reservoir

Since 2022, the SPM photometer has been continuously monitoring optical characteristics in the study area, providing background characteristics of atmospheric aerosols over the Gorky Reservoir and Nizhny Novgorod. In the 2016–2017 studies, the background values were considered to be AOD(500) ≈ 0.18 and $\alpha \approx 1.45$, but later regular measurements covering not only the summer period showed that the background values in the study region were lower: AOD(500) = 0.12 and $\alpha = 1.22$ [26]. Analysis of particle size distribution revealed no predominance of particles of a certain size, whether large or small, for background aerosols.

To identify sources of aerosol activity, satellite data were analyzed for all days on which elevated values of atmospheric aerosol optical properties were recorded during *in situ* measurements.

As Fig. 2 shows, the average daily AOD(500) value of 0.28 recorded on 13 April 2022 is the highest one for the entire spring period of 2022. The results of modeling the backward trajectories of air flows for that day using the HYSPLIT model showed the movement of dust aerosol at an altitude of 3 km from the Karakum side. This means that the increase in AOD on 13.04.2022 is due to the presence of dust aerosol in the atmosphere over the region under study.

During the summer of 2022, a significant number of days were observed to have elevated AOD values, with levels exceeding more than twice the annual average



F i g . 2 . Average variability of aerosol optical depth (AOD) at a wavelength of 500 nm: over the Black Sea, the Southern Coast of Crimea zone and the Kerch Strait, from *AERONET* station data (288 days) (*a*); over the Black Sea, from Section_7 station (Romania) (568 days) (*b*); over the Volga River, from stations data (224 days) (*c*) across the entire spectral range. A thorough analysis of satellite data, complemented by the findings from backward trajectory modeling, revealed that the observed increase in AOD values was predominantly attributable to the presence of smoke aerosols from forest fires, which were localized east of the Gorky Reservoir. The average daily AOD(500) value of 0.39 on 12 April 2023 represents the maximum for the entire measurement period under study. The maximum AOD value (AOD(500) = 0.45) on that day was recorded at 14:00. Satellite data indicates that MAIAC AOD values over the Gorky Reservoir were within the range of (0.4 ± 0.01). The backward trajectories of air flows were simulated using the HYSPLIT software package, with the start time of the simulation set at 14:00 UTC, the time when the maximum AOD values were recorded. The transport area coincided with the area in which the AIRS MODIS/Aqua algorithms determined an increased concentration of dust aerosols. A thorough examination of the contribution of coarse and fine aerosol particles to the total AOD(500) revealed that elevated AOD values were predominantly attributable to the presence of fine particles, which constituted up to 80% of the total. MAIAC satellite data confirm that AOD values exceed background levels, which is consistent with the results of *in situ* measurements.

The VIIRS Deep Blue algorithm for 24 April 2023 identified the presence of dust particles, as well as mixed and background aerosols (Fig. 3). High Angstrom exponent values for 24–28 April 2023 ($\alpha > 2$) confirm that the elevated AOD values are attributable to the presence of finely dispersed absorbing aerosols in high concentrations.

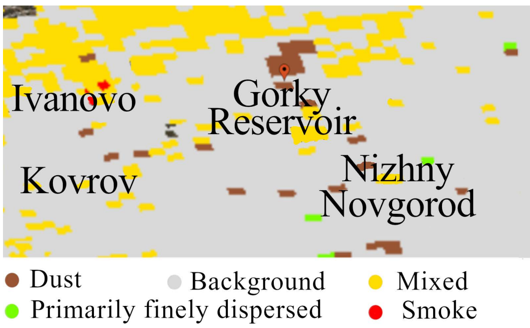


Fig. 3. Satellite images obtained using the VIIRS spectroradiometer (flight time 10:33 UTC) using the VIIRS Deep Blue algorithm for 24 April 2023 (Archive AERDB_L2_VIIRS_NOAA20_NRT doi:10.5067/VIIRS/AERDB_L2_VIIRS_NOAA20_NRT.002; AERDB_L2_VIIRS_NOAA20 doi:10.5067/VIIRS/AERDB_L2_VIIRS_NOAA20.002 (date of access: 20 January 2024)

High AOD values were also recorded at the end of April and the end of July 2023. Analysis of model and satellite data to determine the source of aerosol activity that influenced the variability of AOD values at the end of April 2023 revealed no signs of dust transport or intense fires, when the smoke could have moved into the atmosphere of the region under study.

The values of AOD(500) were determined to be 0.29 on 25 May 2023, at $\alpha = 0.7$. When determining the predominant aerosol type using the VIIRS Deep Blue algorithm, the presence of mixed and fine aerosols was detected on that day.

Statistical analysis revealed that AOD values exceeding the monthly average were observed on 26 of the 226 days of observation. Elevated AOD values were mainly observed on days when smoke and dust aerosols were present in the atmosphere over the study region, but they were also recorded on days when anthropogenic aerosols were detected. In some cases, the origin of aerosol activity could not be ascertained.

Given the absence of documented transport from Africa via the Black Sea during the study period, a direct comparison between the optical characteristics obtained for this reservoir and those of the Black Sea stations was not feasible.

Cheboksary Reservoir

The expedition to the Cheboksary Reservoir was the shortest, with a duration of four days. During this period, AOD(500) values approximating the background values for the Nizhny Novgorod region were obtained (average AOD(500) = 0.11).

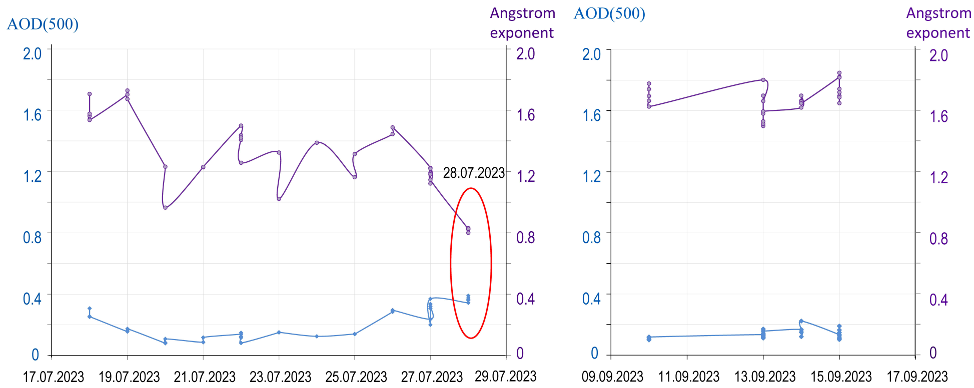
Average Angstrom exponent $\alpha = 1.7$ demonstrates the predominance of fine particles during the study period. This is confirmed by data on particle size distribution: the contribution of the coarse mode is only 21% of the total AOD(500) value.

Analysis of optical characteristic data for the periods 9–10 and 16–17 September 2023 for the Black Sea stations confirmed the presence of fine and background aerosols over the entire Black Sea water area (average AOD(500) values for both stations did not exceed 0.12).

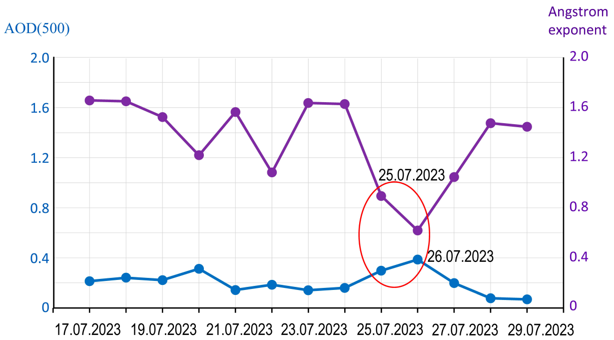
Kuybyshev Reservoir

In this area, high AOD(500) values (twice as high as background levels) were recorded on 26–28 July 2023. During the entire expedition period, the maximum AOD values over the Kuybyshev Reservoir were recorded on 28 July 2023 (average daily AOD(500) value = 0.38, with AOD(500) = 0.43 at 10:00, which is twice the background values for central Russia). On the same day, the Angstrom exponent values were below 1.0 (Fig. 4). An analysis of the particle size distribution revealed that large particles constituted 45% of the total. Such a set of optical characteristics is typically obtained when recording arid aerosol over the region under study.

A comparative analysis of optical characteristics over the same period at the Kuybyshev Reservoir and the Black Sea revealed that two days before the maximum values were recorded over the Volga, high AOD values and low Angstrom exponent values were obtained at the Black Sea AERONET Galata_Platform (AOD(510) = 0.4 and $\alpha = 0.7$) and Sevastopol (AOD(510) = 0.39 and $\alpha = 0.8$) stations. The transport of dust aerosols from Africa towards Crimea and central Russia can last from one day to more than a week. This means that the aerosol recorded on 28 July 2023 over the Kuybyshev Reservoir could have been present in the atmosphere of the Black Sea on 26 July. This assumption can be confirmed by the results of HYSPLIT modeling of backward and forward air flow trajectories. Over the Black Sea, the maximum daily values of the AOD and the minimum values of the Angstrom exponent were recorded at 14:00 UTC at the Galata_Platform station (AOD(510) = 0.48; $\alpha = 0.48$) and at 16:00 at the Sevastopol station (AOD(500) = 0.4; $\alpha = 0.66$). Over the Black Sea, the maximum daily values of the AOD and the minimum values of the Angstrom exponent were recorded at 14:00 UTC at the Galata_Platform station (AOD(510) = 0.48; $\alpha = 0.48$) and at 16:00 at the Sevastopol station ((AOD(500) = 0.4; $\alpha = 0.66$). A thorough analysis



a



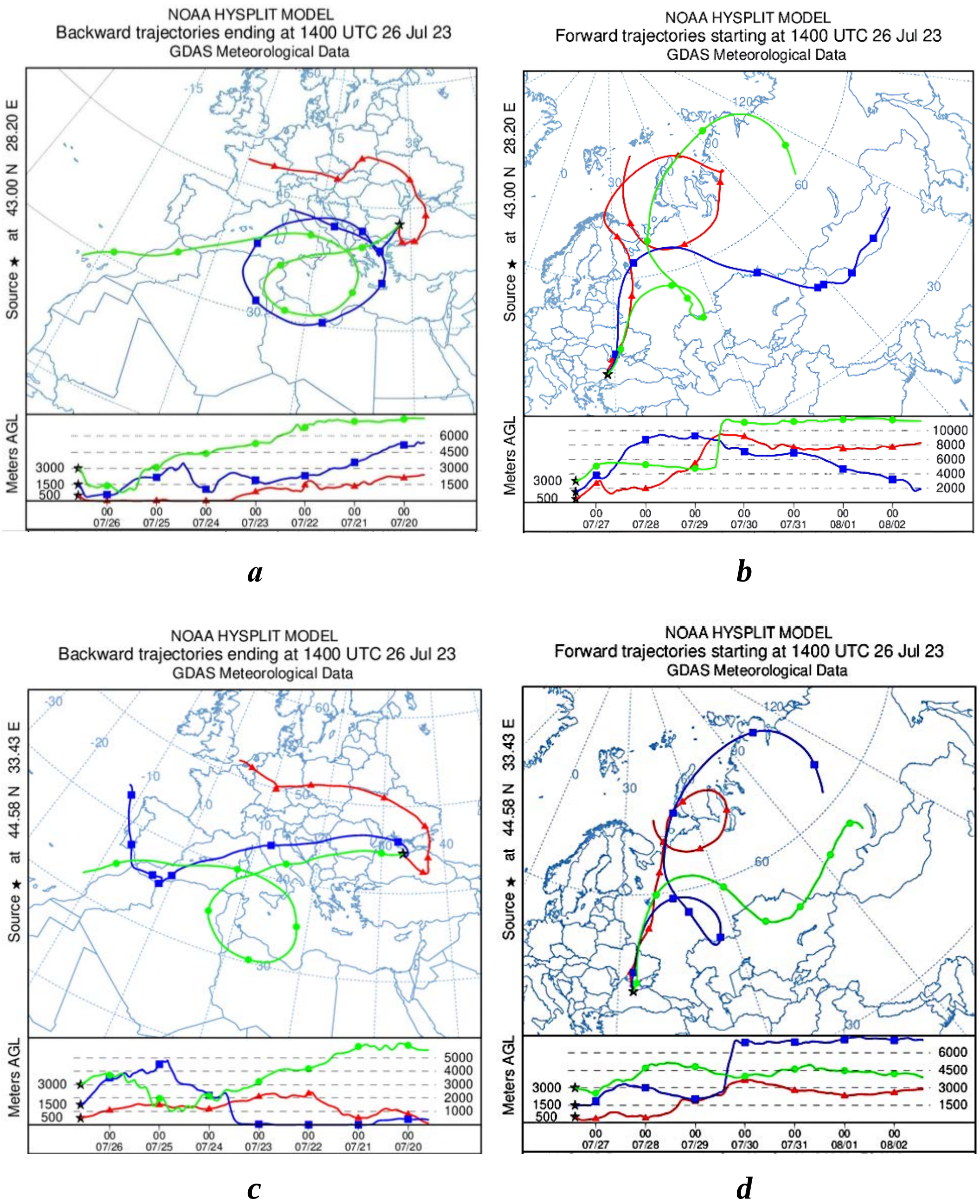
b

F i g . 4 . Variability of the AOD and the Angstrom exponent during the expeditions over the Kuybyshev Reservoir (*a*) and over the Black Sea (*b*). The red ellipses denote cases of high AOD values and low Angstrom exponent values

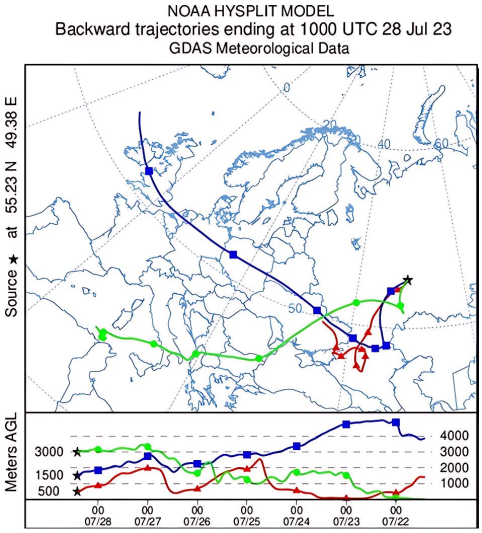
of the variability of optical characteristics during the movement of dust aerosol over the Black Sea stations and over the Kuybyshev Reservoir indicates that the aerosol has not undergone any changes in composition or properties. The optical characteristics obtained on 26 July 2023 over Sevastopol and on 28 July over the Kuybyshev Reservoir differ minimally. Taking into account the distance from the Black Sea Galata_Platform and Sevastopol stations to the Kuybyshev Reservoir (~ 2000 km), the speed of dust aerosol movement was determined (~ 50 km/h).

Given the highest AOD(500) values over the Kuybyshev Reservoir were obtained on 28 July 2023 in the morning hours, the backward trajectories of air flows were calculated using the HYSPLIT model for 10:00 UTC. Analysis of modeling data revealed that at an altitude of 3 km, air mass transfer from the Sahara Desert is recorded (Fig. 5, *b*). As can be seen, based on the backward trajectories of air masses, the transfer from Africa was recorded both over the Black Sea AERONET stations (Fig. 5, *a*, *c*) and over the Kuybyshev Reservoir (Fig. 5, *e*).

The results of forward transport modeling confirm the presence of an air mass that was located over the Black Sea at an altitude of 3 km on 26 July 2023 and appeared over the Volga region on 28 July (Fig. 5, *b*, *d*).



F i g . 5 . HYSPLIT air flow simulation data: backward (*a*) and forward (*b*) trajectories for Galata_Platform station; backward (*c*) and forward (*d*) trajectories for Sevastopol station for 26 July 2023; backward trajectories for Kuybyshev Reservoir for 28 July 2023 (*e*)



e

Continued Fig. 5

A satellite image of the Black Sea central part also shows a trail of haze, which can be dust aerosol transported from Africa. Satellite AOD measurements are not available for the Volga River. However, AOD values in the coastal region exceed background levels and exhibit minimal variation from the *in situ* SPM data for that particular day (according to MODIS data, AOD(500) values range from 0.35 to 0.36). To confirm the presence of a dust aerosol source, the CALIPSO satellite data were analyzed (Fig. 6).

1A thorough analysis of aerosol type data employing the CALIPSO satellite algorithm over the specified water body revealed the presence of substantial amounts of both polluted and clean dust aerosol. In conclusion, the results of both modeling and remote sensing confirm that the elevated AOD values, low Angstrom exponent values and high concentration of large aerosol particles are due to the presence of arid-origin particles in the atmosphere. A comprehensive analysis of the spatio-temporal variability of the optical properties of aerosols over the Kuybyshev Reservoir and the Black Sea it indicated that during intense dust transport from the Sahara Desert, the characteristics of aerosols remained constant, despite the difference in the time of their detection over the regions.

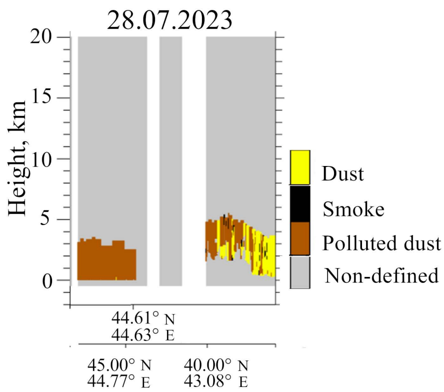


Fig. 6. CALIPSO satellite data for 28 July 2023

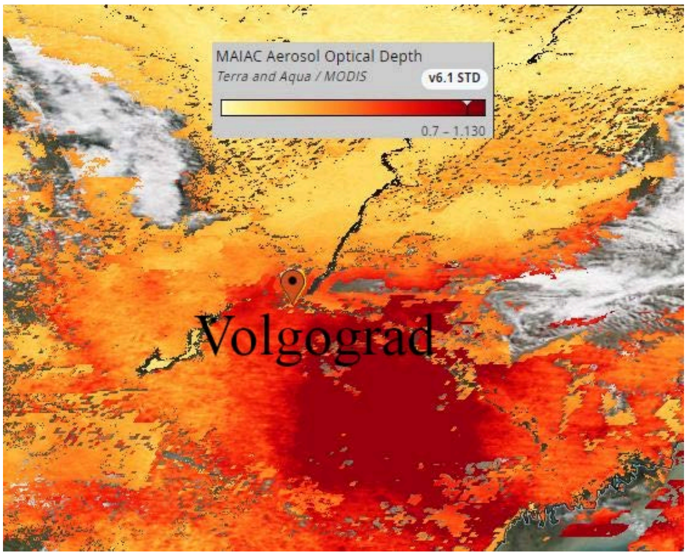
Consequently, upon detection of dust aerosols over the Volga River reservoirs, regional algorithms can be implemented to restore water brightness coefficients for the Black Sea.

Expedition data on this reservoir were obtained during the period from 31 May 2024 to 5 June 2024. The average values of the main optical characteristics for the study period were: AOD(500) = 0.16; $\alpha = 1$. On 31 May 2024, $\alpha = 0.4$, and the AOD values across the entire spectral range were at an average level.

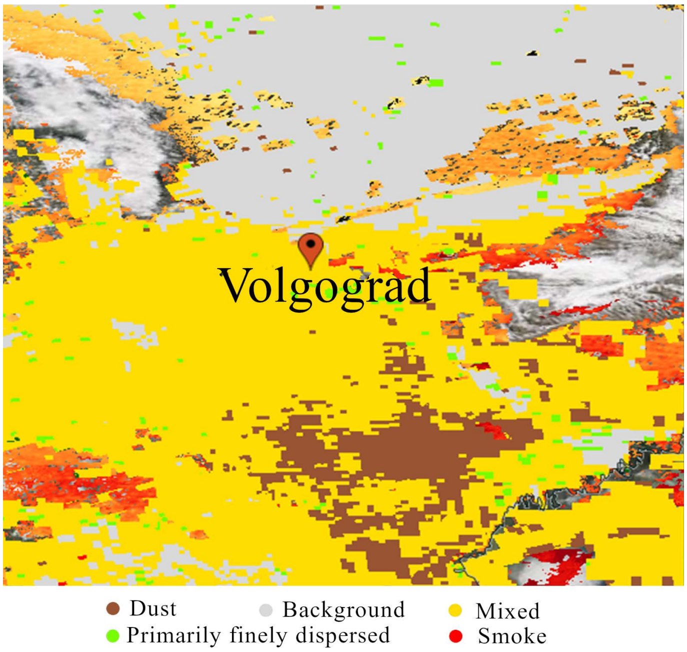
Satellite (MODIS and VIIRS) measurements of the AOD for 31 May 2023 confirmed the presence of an area with elevated values southwest of the Volgograd Reservoir (Republic of Kalmykia) (Fig. 7). Analysis of backward trajectories based on HYSPLIT modeling results showed the transport of dust aerosols from the Karakum Desert on 30–31 May 2024.

Analysis of VIIRS and Aqua/MODIS satellite images (True Color channel) for 31 May 2024 over the Volgograd Reservoir revealed variable cloud cover during the flyovers of satellites at 10:02 and 10:28 UTC, respectively. The clearest image with minimal cloud cover was obtained using Terra/MODIS (True Color) at 7:24 UTC. It is well established that dust particles facilitate the process of moisture coagulation, leading to the formation of clouds comprising both fine and coarse dust aerosol fractions subsequent to the dust aerosol passage [27, 28]. The results of wind speed modeling using the ICON software package [29] at all altitudes up to 1500 m demonstrated transport from the Karakum Desert. The maximum wind transport intensity was documented at an altitude of 500 m (Fig. 8), which corresponded to the results of the HYSPLIT backward trajectory modeling.

The expedition measurements for the study period from 31 May 2024 to 7 June 2024, obtained over the Volgograd Reservoir, were compared with data from simultaneous observations over the Black Sea. Since the elevated AOD values over the Volgograd Reservoir recorded on 31 May 2024 were caused by the advection of dust aerosols from the Karakum Desert, air currents over the Black Sea prior to this event were not considered. However, it is noteworthy that on 4 and 5 July 2024, abnormally high AOD values were recorded over the Black Sea, with maximum values of AOD(500) = 0.3 and AOD(500) = 0.29, respectively. These values are more than one and a half times higher than the standard background levels. On these dates, measurements were obtained using an SPM photometer aboard R/V *Professor Vodyanitsky* (during its 131st voyage). A comprehensive analysis of *in situ* photometric measurements, VIIRS satellite data and HYSPLIT air flow modeling results confirmed the transport of dust aerosols to the study region (Fig. 9). Despite the fact that dust aerosol transport from Africa is frequently observed over the Black Sea during the spring and summer months, it is challenging to make an unequivocal quantitative evaluation of their contribution to the sea surface brightness coefficient in May and June for this region due to the coinciding intense phytoplankton bloom, which also results in a substantial increase in this parameter [30].

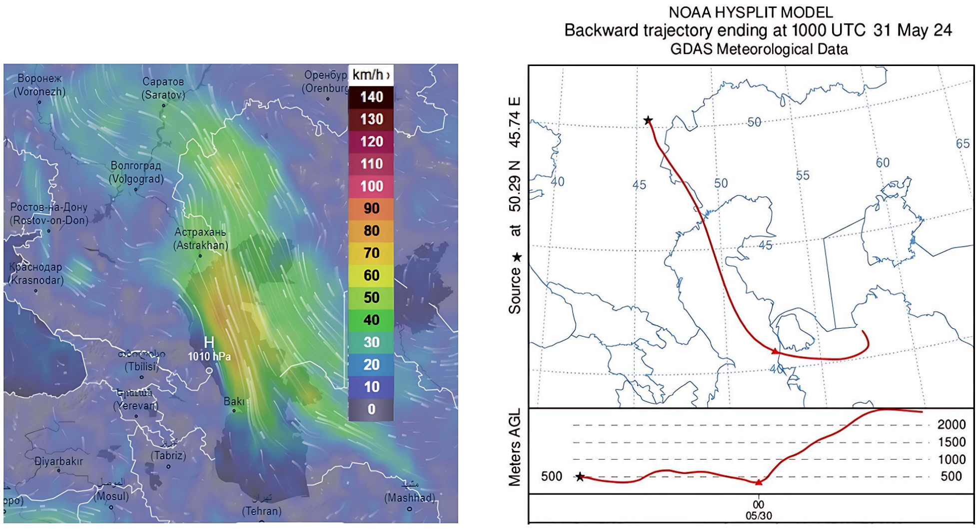


a



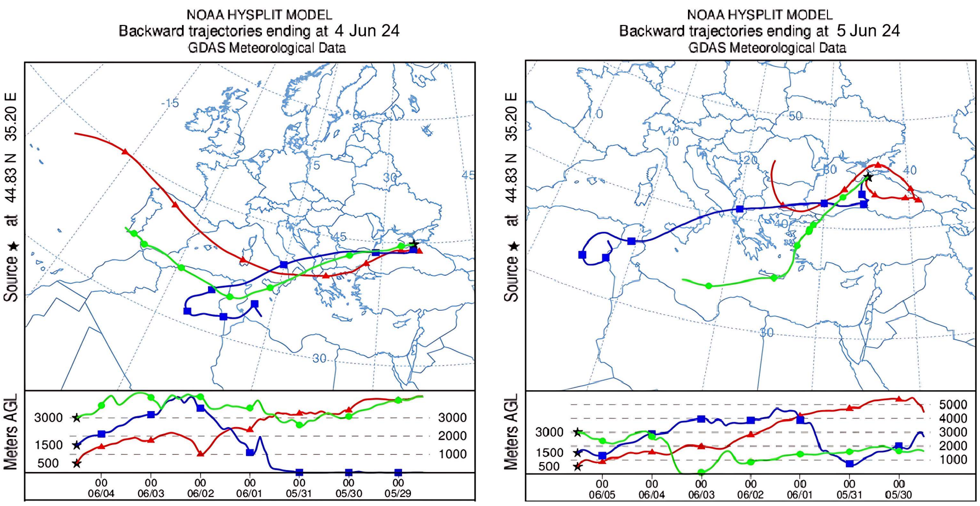
b

F i g . 7 . Satellite data of MODIS (flight time 10:28 UTC) and VIIRS (flight time 10:02 UTC) for 30 May 2024: AOD distribution from the MAIAC algorithm (*a*), aerosol type determination from the VIIRS Deep Blue algorithm (*b*)



a ***b***

F i g . 8 . The results of modeling wind speeds according to the ICON model (*a*); backward trajectories of air flow movement according to the HYSPLIT model (*b*) at an altitude of 500 m



a ***b***

F i g . 9 . The results of backward trajectories of air flow movement modeling according to the HYSPLIT model for 4 June 2024 (*a*) and 5 June 2024 (*b*)

Conclusion

A comparative analysis of the primary optical characteristics of the atmosphere above the Black Sea and four reservoirs on the Volga River was conducted, resulting in the identification of periods with background values and episodes with abnormally high AOD values. For these periods, a detailed analysis of satellite data and the results of air flow modeling was performed. In the majority of cases, the increase in AOD values in the studied regions was explained by dust aerosol advection. A comprehensive study of the transport of dust from the African continent has led to the identification of the temporal patterns of dust aerosol movement across the Black Sea towards the Kuybyshev Reservoir. Taking into account the distance between the Black Sea Galata_Platform and Sevastopol stations, and the Kuybyshev Reservoir, the average speed of dust aerosol movement was calculated (~ 50 km/h). The spring and summer periods have been identified as those of high AOD values and low Angstrom exponent over the Black Sea and the Volga River region. An important result of this study is the invariability of the optical characteristics of aerosols over the Black Sea and the Kuybyshev Reservoir during episodes of intense dust transport from the Sahara Desert. This indicates the possibility of using regional algorithms developed for the Black Sea to restore brightness coefficients based on satellite data over the Volga River reservoirs, considering the presence of dust aerosol.

REFERENCES

1. Rozenberg, G.V., Gorchakov, G.I., Georgievskiy, Yu.S. and Lyubovtseva, Yu.S., 1980. [Optical Parameters of Atmospheric Aerosol]. In: G. S. Golitsyn and A. M. Yaglom, eds., 1980. [*Atmospheric Physics and Climate Problems*]. Moscow: Nauka, pp. 216–257 (in Russian).
2. Ginzburg, A.S., Gubanova, D.P. and Minashkin, V.M. Influence of Natural and Anthropogenic Aerosols on Global and Regional Climate. *Russian Journal of General Chemistry*, 79, pp. 2062–2070. https://doi.org/10.1134/S1070363209090382
3. Kondratyev, K.Ya., 2004. Atmospheric Aerosol as a Climate Forming Component of the Atmosphere. 1. Properties of Various Types of Aerosols. *Optika Atmosfery i Okeana*, 17(1), pp. 5–24 (in Russian).
4. Lisitzin, A.P., 2011. Arid Sedimentation in the Oceans and Atmospheric Particulate Matter. *Russian Geology and Geophysics*, 52(10), pp. 1100–1133. https://doi.org/10.1016/j.rgg.2011.09.006
5. Bukharina, I.L., Zhuravleva, A.N. and Bolshova, O.G., 2012. [*Urban Planting: Ecological Aspect*]. Izhevsk: Udmurtskiy Gos. Un-t, 204 p. (in Russian).
6. Tsalikov, R.H., Akimov, V.A. and Kozlov, K.A., 2009. [*Assessment of Natural, Technogenic and Ecological Security of Russia*]. Moscow: BNII GOChS, 464 p. (in Russian).
7. Tomilina, I.I., Gapeeva, M.V. and Lozhkina, R.A., 2018. Assessment of Water Quality and Bottom Sediments of the Volga River Reservoirs Based on Toxicity and Chemical Composition. *Transactions of Papanin Institute for Biology of Inland Waters RAS*, (82), pp. 107–131 (in Russian).
8. Koposov, E.V., Paleev, A.V., Sobol, S,V., Vinogradova, T.P., Kaschenko, O.V., Katraeva, I.V., Ivanov, A.V., Panyutin, A.A., Ryzhova, T.S. and Vinogradov, M.A., 2008. [*Environmentally Safe, Sustainable Development of the Volga Basin: Aspects of International Scientific Cooperation*]. Nizhniy Novgorod: NNGASU, 178 p. (in Russian).

9. Monin, A.S. and Shishkov, Yu.A., 2000. Climate as a Problem in Physics. *Physics-Uspekhi*, 170(4), pp. 444–445. https://doi.org/0.1070/PU2000v043n04ABEH000678
10. Sverdlik, L.G., 2014. Peculiarities of Absorbing Aerosol Radiative Properties. *Science and New Technologies*, (4), pp. 26–31 (in Russian).
11. Yakovleva, I.P. and Tashchilin, M.A., 2022. Aerosol Optical Depth Spectral Characteristics Under Exposure to Forest Fire Smoke in the Baikal Region. In: I. P. Yakovleva, ed., 2022. *Proceedings of the XVII Young Scientists' Conference "Interaction of Fields and Radiation with Matter"*. Irkutsk: ISTP SB RAS, pp. 343–344 (in Russian).
12. Luzhetskaya, A.P. and Poddubny, V.A., 2019. Features of Temporal Variability of Aerosol Optical Depth in the Middle Urals According to Long-Term Observations at the Urban and Background Sites. *Optika Atmosfery i Okeana*, 32(11), pp. 889–895. https://doi.org/10.15372/AOO20191102 (in Russian).
13. Gorchakova, I.A., Tarasova, T.A., Sviridenkov, M.A., Anikin, P.P. and Romashova, E.V., 2009. Modeling Radiative Forcing by Background Aerosol on the Basis of Measurement Data. *Izvestiya, Atmospheric and Oceanic Physics*, 45(4), pp. 467–477. https://doi.org/10.1134/S0001433809040070
14. Zhuravleva, T.B., Kabanov, D.M., Nasrtdinov, I.M., Russkova, T.V., Sakerin, S.M., Smirnov, A. and Holben, B.N., 2017. Radiative Characteristics of Aerosol During Extreme Fire Event over Siberia in Summer 2012. *Atmospheric Measurement Techniques*, 10(1), pp. 179–198. https://doi.org/10.5194/amt-10-179-2017
15. Holben, B.N., Eck, T.F., Slutsker, I., Tanré, D., Buis, J.P., Setzer, A., Vermote, E., Reagan, J.A., Kaufman, Y.J. [et al.] 1998. AERONET – A Federated Instrument Network and Data Archive for Aerosol Characterization. *Remote Sensing of Environment*, 66(1), pp. 1–16. https://doi.org/10.1016/S0034-4257(98)00031-5
16. Sakerin, S.M., Kabanov, D.M., Rostov, A.P., Turchinovich, S.A. and Turchinovich, Yu.S., 2004. System for Network Monitoring of Radiatively Active Atmospheric Constituents. Part I. Sun Photometers. *Optika Atmosfery i Okeana*, 17(4), pp. 354–360 (in Russian).
17. Kabanov, D.M. and Sakerin, S.M., 1995. Results of Investigation of Total Moisture Content in the Atmosphere by Optical Hygrometry Method. Part 1. Analysis of the Method and Calibration Results. *Optika Atmosfery i Okeana*, (6), pp. 852–860 (in Russian).
18. Kabanov, D.M., Veretennikov, V.V., Voronina, Y.V., Sakerin, S.M. and Turchinovich, Y.S., 2009. Information System for Network Solar Photometers. *Atmospheric and Oceanic Optics*, 22(1), pp. 121–127. https://doi.org/10.1134/S1024856009010187
19. Lyapustin, A. and Wang, Y., 2007. *MAIAC-Multi-Angle Implementation of Atmospheric Correction for MODIS*. NASA, 77 p.
20. Wang, W., Mao, F., Pan, Z., Du, L. and Gong, W., 2017. Validation of VIIRS AOD Through a Comparison with a Sun Photometer and MODIS AODs over Wuhan. *Remote Sensing*, 9(5), 403. https://doi.org/10.3390/rs9050403
21. Cao, C., Xiong, J., B;onski, S., Liu, Q., Uprety, S., Shao, X., Bai, Y. and Weng, F., 2013. Suomi NPP VIIRS Sensor Data Record Verification, Validation, and Long-Term Performance Monitoring. *Journal of Geophysical Research: Atmospheres*, 118(20), pp. 11664–11678. https://doi.org/10.1002/2013JD020418
22. Lee, J., Hsu, N.C., Kim, W.V., Sayer, A.M. and Tsay, S.-C., 2024. VIIRS Version 2 Deep Blue Aerosol Products. *Journal of Geophysical Research: Atmospheres*, 129(6), e2023JD040082. https://doi.org/10.1029/2023JD040082
23. Hsu, N.C., Tsay, S.-C., King, M.D. and Herman, J.R., 2004. Aerosol Properties over Bright-Reflecting Source Regions. *IEEE Transactions on Geoscience and Remote Sensing*, 42(3), pp. 557–569. https://doi.org/10.1109/TGRS.2004.824067

24. Hsu, N.C., Jeong, M.-J., Bettenhausen, C., Sayer, A.M., Hansell, R., Seftor, C.S., Huang, J. and Tsay, S.-C., 2013. Enhanced Deep Blue Aerosol Retrieval Algorithm: The Second Generation. *Journal of Geophysical Research: Atmospheres*, 118(16), pp. 9296–9315. https://doi.org/10.1002/jgrd.50712
25. Kalinskaya, D.V. and Papkova, A.S., 2019. Correlation of the Atmospheric Aerosol Optical Characteristics Data by CALIPSO and MODIS Satellites Measurements and SPM Photometer. In: IO RAS, 2019. *Proceedings of X Anniversary All-Russia Conference «Current problems in optics of natural waters» (ONW'2019)*. Saint-Petersburg: KHIMIZDAT. Vol. 10, pp. 283–287 (in Russian).
26. Kalinskaya, D.V. and Molkov, A.A., 2023. Spatio-Temporal Variability of the Aerosol Optical Depth over the Gorky and Cheboksary Reservoirs in 2022–2023. *Remote Sensing*, 15(23), 5455. https://doi.org/10.3390/rs15235455
27. Izmailova, A.V., 2016. Water Resources of the Lakes of Russia. *Geography and Natural Resources*, 37(4), pp. 281–289. https://doi.org/10.1134/S1875372816040016
28. Varenik, A.V., Kalinskaya, D.V., Myslina, M.A. and Khoruzhy, D.S., 2019. [Changes in the Nutrients Content in the Seawater Surface Layer after Atmospheric Precipitation]. In: MHI, 2019. [*Proceedings of the All-Russia Scientific Conference: Seas of Russia: Fundamental and Applied Research. Sevastopol, 23–28 September 2019*]. Sevastopol: MHI, pp. 51–52 (in Russian).
29. Sofiev, M., Vira, J., Kouznetsov, R., Prank, M., Soares, J. and Genikhovich, E., 2015. Construction of the SILAM Eulerian Atmospheric Dispersion Model Based on the Advection Algorithm of Michael Galperin. *Geoscientific Model Development*, 8(11), pp. 3497–3522. https://doi.org/10.5194/gmd-8-3497-2015
30. Churilova, T.Ya. and Suslin, V.V., 2012. On Causes of *Emiliania huxleyi* Domination in Phytoplankton of Deep Waters Part of the Black Sea in Early Summer. In: MHI, 2012. *Ekologicheskaya Bezopasnost' Pribrezhnoy i Shel'fovoy Zon i Kompleksnoe Ispol'zovanie Resursov Shel'fa* [Ecological Safety of Coastal and Shelf Zones and Comprehensive Use of Shelf Resources]. Sevastopol: MHI. Iss. 26(2), pp. 195–203 (in Russian).

Submitted 21.01.2025; accepted after review 11.03.2025;
revised 24.06.2025; published 30.09.2025

About the authors:

Daria V. Kalinskaya, Junior Research Associate, Marine Hydrophysical Institute of RAS (2 Kapitanskaya Str., Sevastopol, 299011, Russian Federation), **Scopus Author ID: 56380591500**, *kalinskaya@mhi-ras.ru*

Aleksandr A. Molkov, Senior Research Associate, A.V. Gaponov-Grekhov Institute of Applied Physics of RAS (46 Ulianova Str., Nizhny Novgorod, 603950, Russian Federation), PhD (Phys.-Math.), **Scopus Author ID: 55377777800**, **ResearcherID: A-3623-2014**, *a.molkov@inbox.ru*

Contribution of the authors:

Daria V. Kalinskaya – photometric measurements over the Black Sea, data processing, article text writing, text editing

Aleksandr A. Molkov – photometric measurements over the Volga River reservoirs

All the authors have read and approved the final manuscript.