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Impact of the Cyclone on Spatial Distribution of the Smoke Aerosol Resulted from the Fires in May, 2021

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Abstract

Purpose. Using the satellite and ground-based monitoring, as well as the results of modeling the atmosphere dynamics, a long-range transport of smoke aerosol was comprehensively studied.

Methods and Results. The period of multiple and intense fires recorded in Western Siberia near the Kazakhstan border in May, 2021 was considered. To analyze the scales and locations of the most active fires during the period under consideration, the satellite monitoring maps from the FIRMS system archives were used. Being analyzed, the satellite images showed the smoke transfer on May, 9 and 10 towards the Middle Urals that was confirmed by photometric measurements at the AERONET aerial ash monitoring station. The results of modeling the air mass back transfer performed due to the HYSPLIT software were represented to confirm smoke transport from the Urals. On May, 11 a cyclone was formed over the territory of the Volgograd region, its periphery just covered the Urals region. This fact contributed to the smoke aerosol transfer towards Finland at a distance exceeding 4000 km via the Black Sea region. The basic information on the stages of the cyclonic vorticity formation and the smoke aerosol transport was obtained from the MODIS Aqua, VIIRS and CALIPSO satellite platforms. Based on the VIIRS satellite data, the dynamics of the surface layer temperature variability and the chlorophyll a concentration in the zone of the maximum wind impact in the Black Sea region before and after the cyclone passage were analyzed. The main optical and microphysical characteristics of the atmosphere aerosol for the period under study were also analyzed using the data from a portable sun photometer and the AERONET stationary ones.

Conclusions. A number of specific meteorological conditions which developed in May, 2021 promoted accumulation of the smoke aerosol in the atmosphere of the Middle Urals and its subsequent transport, first, to the Black Sea region and then – towards Finland.

Keywords: FIRMS, MODIS, VIIRS, SPM, AERONET, CALIPSO, back trajectories, HYSPLIT, Black Sea, atmospheric aerosol, fire, satellite monitoring, land monitoring, aerosol optical depth, MAIAC, optical characteristics

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Introduction

An accurate assessment of the aerosol radiative impact on the climate system is complicated by the lack of information on their temporal and spatial variability, as well as on their optical and microphysical properties [1, 2]. To understand the dynamics of aerosol distribution, it is necessary to study the influence of aerosols of various types on global and regional climate changes. One of the advantages of the remote research method is its extensive spatial coverage. At the same time, atmospheric inhomogeneities (cloudiness, stratification, atmospheric pressure variability, and temperature inversion) can significantly impact the quality of the received satellite data and, subsequently, the results of their analysis [1].

Ground-based measurements provide the correction of those inaccuracies in determining the optical characteristics obtained by remote methods, which were caused by the variability and anomalies of these characteristics. However, local measurements at an individual station do not fully describe the distribution of aerosols over a water area or a terrestrial region due to the significant spatial and temporal inhomogeneity of aerosol particles in the atmosphere. Thus, a comparison of satellite and ground-based observational data makes it possible to reconstruct a more complete picture of the distribution of the atmosphere's optical characteristics and evaluate both local and global cases of aerosol impact on climate change (see the work [2] and papers [2, 3]).

The main objectives of space monitoring of fires are their prompt identification and the assessment of areas affected by fires. To solve these problems, MODIS (Moderate Resolution Imaging Spectro Radiometer) remote sensing data from the Aqua and Terra satellites [4] are used as basic data, and for clarification, the data from field measurements of the optical parameters of the underlying surface atmosphere are used.

Instruments and materials

The aerosol optical depth (AOD) of the atmosphere is calculated according to the Bouguer law from the spectral attenuation of direct solar radiation. For determining the AOD, the attenuation of light due to molecular Rayleigh scattering and absorption by gaseous constituents of the atmosphere, which is then subtracted from the total optical depth of the atmosphere, is calculated. Photometer measurementsare used to calculate the AOD at wavelengths λ, except for the 936 nm channel, which measures the water vapor content in the atmospheric column [5, 6]. The AOD is an indicator of the variability of the atmosphere's optical properties due to the correlation between the concentrations of aerosol particles and the light attenuation coefficients.The data on them are obtained due to the widespread use of satellite remote sensing methods [2].

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[1] Matveev, L.T., 1984. [*The Course of General Meteorology, Physics of Atmosphere and Ocean*]. Leningrad: Gidrometeoizdat, 752 p. (in Russian).

[2] Ivlev, L.S., 2015. [Influence of the Atmospheric Aerosols on Global and Regional Climate of the Earth]. In: [*Modeling and Situational Management of the Quality of Complex Systems*]. Saint Petersburg: SPSUAI, pp. 117-119 (in Russian).

Three types of atmospheric AOD data were used in the work: measurement data obtained from the Terra and Aqua satellites by the MODIS spectroradiometer [4], ground-based observations measured by the SPM portable photometer [7] for Sevastopol station, and photometer data from the stations of the AERONET international aerosol monitoring network [8, 9].

Owing to the MODIS Aerosol Optical Depth (AOD) L2 satellite product, an accurate synoptic view of the aerosol loading level in the atmosphere can be obtained. Aerosols absorb and scatter incoming sunlight, which reduces visibility and increases the AOD. Aerosols also affect the weather and climate by contributing to the Earth's cooling or warming, helping or preventing cloud formation [10]. L3 satellite data are quantitative information. These data are used to predict the aerosol impacts in various models.

The AOD estimates obtained using the MAIAC (Multi-Angle Implementation of Atmospheric Correction) algorithm characterize the magnitude of aerosol absorption and scattering in the entire atmospheric column [3]. In order to determine the AOD spatial and temporal features for the Black Sea region, it was the data calculated using the MAIAC satellite algorithm that were used, since they have a high spatial resolution and are available for the measurement period of the MODIS radiometer. A comparative analysis of these data and the data of the Black Sea stations of the AERONET network revealed that the data obtained using the MAIAC algorithm have smaller discrepancies with the data of ground-based measurements compared to other MODIS aerosol products. Currently, the MAIAC is the only algorithm that provides high-quality aerosol information with 1 km spatial resolution, including small-scale urban pollution, smoke from active fires (including small localized fires), and dust storms. MAIAC products capture and accurately type aerosols from most active fires, which are often recognized as clouds in standard operational atmospheric correction algorithms. With good accuracy on all types of underlying terrain, including bright snowy and urban surfaces, the MAIACAOD product is widely used for air quality monitoring worldwide. The MAIAC provides data in partly cloudy conditions [3] where standard coarse resolution products cannot provide reliable information about the optical characteristics of the atmospheric layer [4].

AOT from MODIS and MAIAC data is the result of a combination of measurements from the Terra and Aqua satellites, information on which is provided near real time. At the same time, the MODIS sensor resolution is 0.5 degrees, the image resolution is 2 km, the temporal resolution is daily, and for the MAIAC products the sensor resolution is 1 km, the image resolution is 1 km, and the temporal resolution is daily [4].

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[3] Lyapustin, A. and Wang, Y., 2008. *MAIAC: Multi-Angle Implementation of Atmospheric Correction for MODIS: Algorithm Theoretical Basis Document (ver. 1.0).* [online] Available at: https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/modis/MAIAC_ATBD_v1.pdf [Accessed: 23 May 2022].

[4] Krasnoshchekov, K.V. and Yakubailik, O.E., 2020. Assessment of Atmospheric Air Quality Using Satellite Data. In: SFU, 2020. *Proceedings of VII Regional Problems of Earth Remote Sensing (RPERS 2020).* Krasnoyarsk: Siberian Federal University, pp. 236-239 (in Russian).

In order to compare satellite and ground-based measurements to correct inaccuracies caused by variability and anomalies of atmospheric parameters, data from the AERONET international network of photometers, which are freely available at http://aeronet.gsfc.nasa.gov [11], were selected.

For the Black Sea region, ground-based monitoring was carried out using the SPM solar photometer – a portable device for measuring the spectral transparency of the atmosphere. The determination of the required atmosphere characteristics is based on the spectral transparencymethod – photometry of direct solar radiation that has passed through the atmosphere [5], and a differential technique [7, 12, 13].

Satellite monitoring maps of active fires obtained from the FIRMS system (URL: https://firms.modaps.eosdis.nasa.gov) archives were used to determine the location and extent of fires.

For determining the predominant type of aerosol for the period under study, we analyzed satellite data from CALIPSO, an American-French research satellite launched as part of the NASA EOS (Earth Observing System) program designed to study the Earth's cloud cover and the vertical structure of atmospheric aerosol. The main measuring instrument of CALIPSO is a three-channel imaging radiometer (8.65 µm, 10.6 µm, and 12.05 µm). CALIPSO measurements can be used to reconstruct the vertical structure of the atmosphere, as well as to determine the predominant type of aerosol over the region under study.

The types of aerosols are determined by the magnitude of the integrated backscatter coefficient and the particle depolarization coefficient. Aerosol types determined by CALIPSO algorithms are the following: smoke (from burning biomass), dust, polluted dust (mixtures of dust and smoke), polluted continental and pure continental aerosol [14, 15]. Each type of aerosol is characterized by a set of lidar ratios at wavelengths of 532 and 1064 nm. Lidar ratios are calculated from typical distributions of particle sizes and complex refractive indices [16–17].

To obtain information about the smoke aerosol source, the results of calculating the reverse trajectories of air mass transfer obtained using the software package of the HYSPLIT model were used. The analysis of reverse trajectories provides the tracking of air flows' movement at different heights and determines the location of probable sources of impurities entering the atmosphere [16–18].

Results

Smoke from large forest fires has a strong impact on the radiative characteristics of the atmosphere and is an important component of optical weather

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[5] Vasiliev, M.S., 2018. [Studies of Atmospheric Aerosol and Water Vapor in Yakutia by Methods of Spectral Solar Photometry]. In: NEFU, 2018. [*Proceedings of the XIX All-Russian Scientific-Practical Conference of Young Scientists, Graduate Students and Students in Neryungri, with International Participation*]. Neryungri: Technical Institute of NEFU Publ., pp. 225-228 (in Russian).

in a number of regions. Fires can be considered random episodic phenomena, but for the boreal climatic zone, they are typical [19] during the warm period.

In late April and early May 2021, multiple fires were recorded in the south of the Middle Urals and Western Siberia. The area covered by these fires exceeded 500 km^2. According to the Ural Department for Hydrometeorology and Environmental Monitoring, in many areas in the south of Sverdlovsk Region, the fire danger level has reached emergency class 5. For these regions, such large-scale fires in May are a fairly rare occurrence (the last time the same occurred in 2004 in Kurgan Region, but then the smoke spread in a different direction).

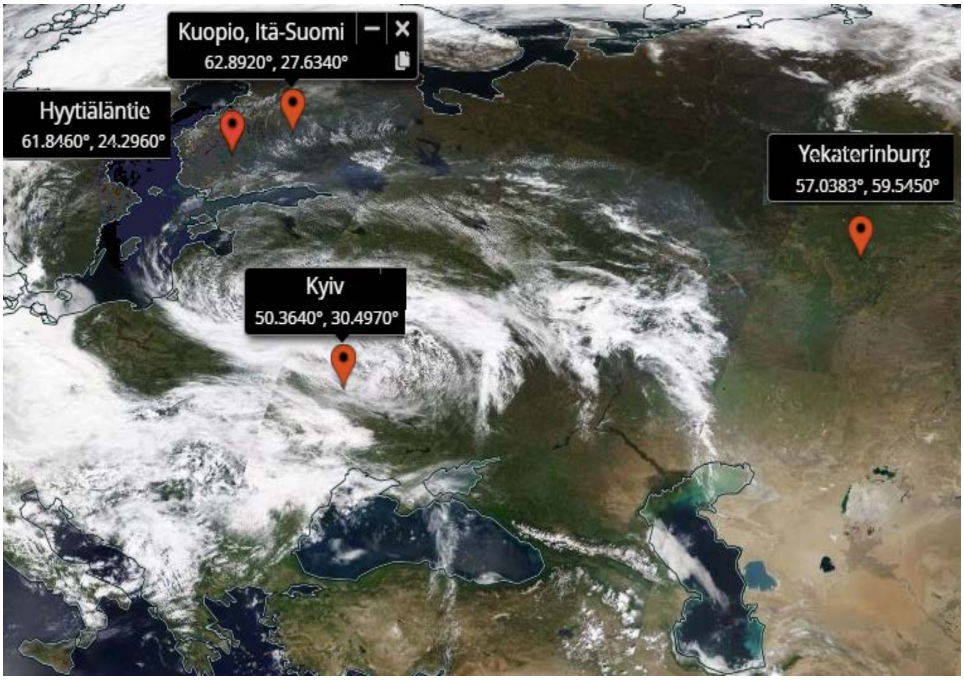
On May 9, favorable conditions for the development of the first stage of the cyclone formed over the territory of the Urals: cold air from the north began to move southward towards warm air, forming the cold front section. At the same time, warm air began to move from the south towards cold air, forming a warm section of the front. As a result of the confluence of the Arctic and Asian anticyclones on May 11, a large anticyclone formed over the territory of the southern Urals, and a cyclone formed over the territory of Volgograd Region with a pressure of 1004 hPa in the center (49.474°N, 45.773°E) and with 1200 km diameter at 5 km height (the estimates were made according to the website https://www.ventusky.com).

According to the GIS-center of Perm State National Research University (http://accident.perm.ru), on May 10, an eastern wind prevailed in the lower part of the troposphere, and combustion products from fires began to spread towards the Urals and further along the western periphery of the anticyclone along the Ural Range to the north.

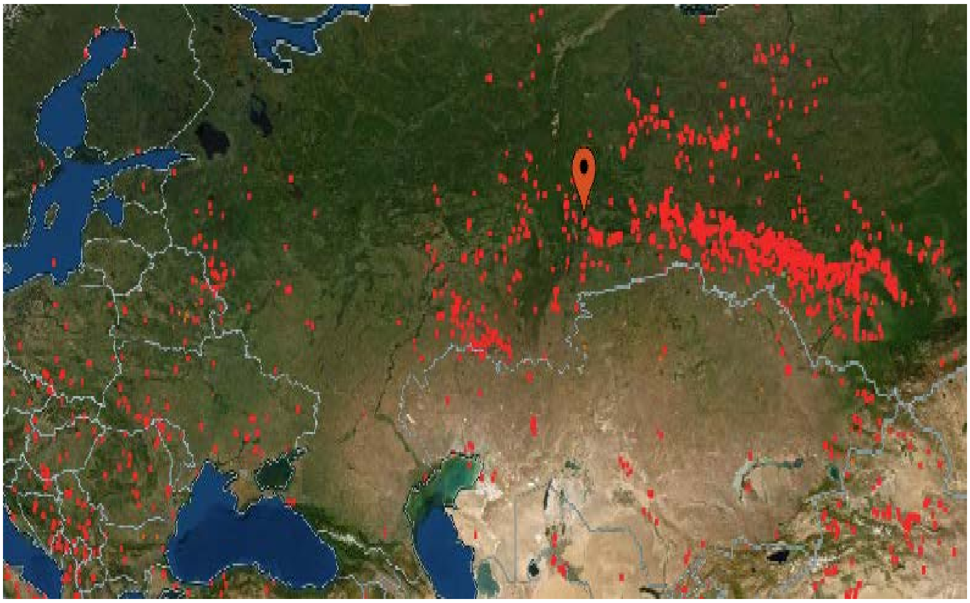
During the day, the cyclone moved at 20 km/h velocity towards Rostov Region, where its maximum intensity was recorded (at 1 km height the maximum orbital velocities reached 100 km/h, and at 100 m height orbital velocities did not exceed 50 km/h). Based on satellite data for May 11, the cyclone dimensions were estimated: its diameter was about 2500 km at 5 km height, and the zone of the spatial impact of the smoke aerosol distribution (estimated from the data for May 13) was about 4000 km (Fig. 1, *a*).

To assess the degree of the cyclone impact on the spatial distribution of smoke from fires in the Urals, the data on the optical characteristics of atmospheric aerosol at AERONET stations were analyzed – at first, directly near the fires before the cyclone appeared (starting from May 9), and then at other stations along the cyclone movement for all days when a haze from fires was observed on satellite images (Fig. 1, *a*).

On May 10, a smoke and a smell of burning were recorded in Yekaterinburg, which was due to a stable atmosphere and weak wind, which did not contribute to the mixing of the surface layer of the atmosphere and its purification.



a



b

Fig. 1. MODIS spectroradiometer-derived satellite image of a smoke plume in natural colors (TrueColor) for May 13, 2021 that reached the territory of Finland (*a*); areas of intense fires according to the FIRMS system for May 9, 2021 (*b*) (https://worldview.earthdata.nasa.gov)

The closest to the fire zone, according to the FIRMS system, was the AERONET Yekaterinburg station (57.03833°N, 59.54500°E), which is pointed with a marker in Fig. 1, *b*. As can be seen from the maps, there are no other such intense and large-scale areas of ignition. The data on the AOD and particle size distribution confirmed the presence of a large number of fine aerosol smoke particles in the atmosphere over the region under consideration. So, for example, on May 10 at the Yekaterinburg station, the average daily AOT value at 500 nm wavelength (AOT (500)) is 1.04, and the maximum value for this day of AOT (500) is 3.2 (AERONET level 1.5 of data processing). In Fig. 2, the marker points to the location of the Yekaterinburg station, and the circle in Fig. 2, *a* denotes the region that was exposed to smoke from fires. As can be seen from Fig. 2, *a*, on May 9, smoke from fires covers the territory of Sverdlovsk Region evenly, but on May 10, an occlusion front forms at the interface of cold continental Arctic air and warm continental tropical air, containing an area of increased smoke aerosol concentrations, i.e. an area of stagnation, which differs from other clouds in density and structure (Fig. 2, *b*).

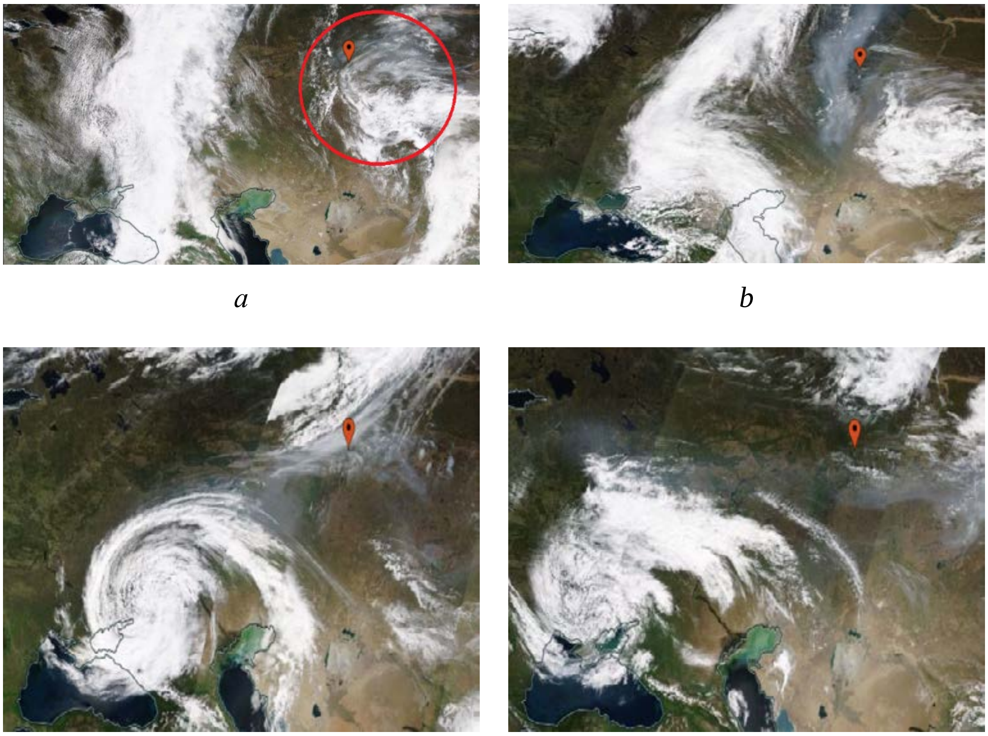

a *b* *c* *d*

Fig. 2. Satellite color-synthesized images in natural colors (*True Color*) obtained using the MODIS spectroradiometer for May, 9 (*a*), May, 10 (*b*), May, 11 (*c*), and May, 12 (*d*), 2021 (https://worldview.earthdata.nasa.gov)

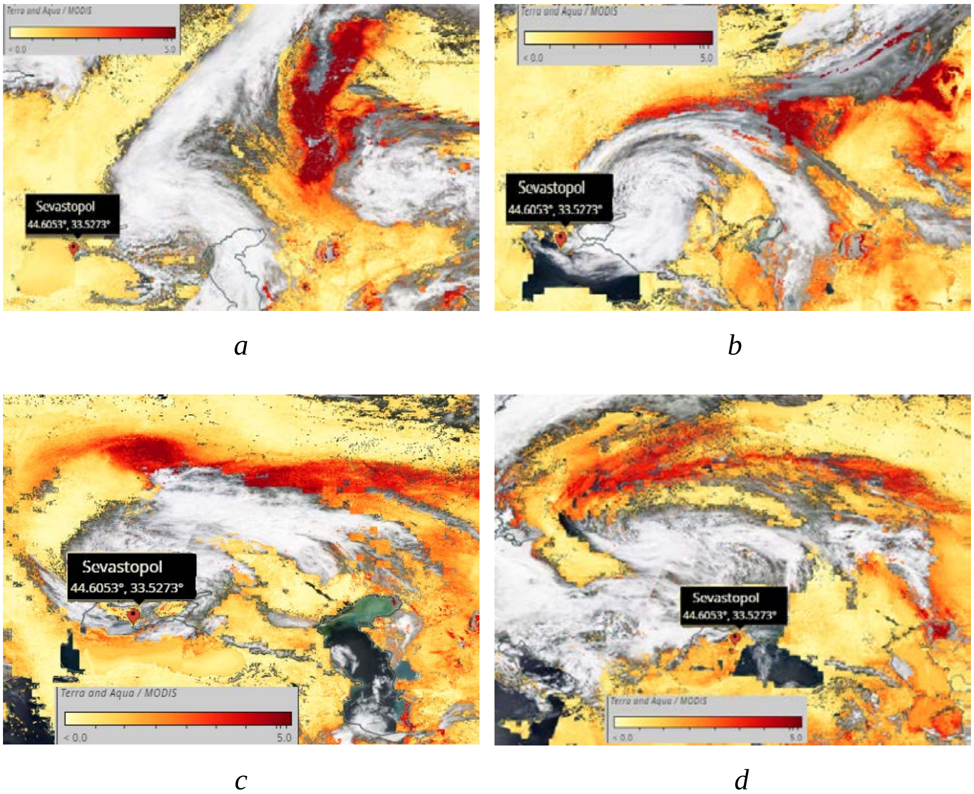
According to the AERONET data, during the cyclone fine particles predominate and low AOT values are observed, which is due to precipitation of the main part of the aerosol under the effect of gravity and inertia. Any particles suspended in the flow inside the cyclone are affected, in addition to the centrifugal force, by the Coriolis force, which tends to displace them from curved current lines along tangents directed at a certain angle downwards and to the periphery.

It is this fact that explains the AOT values obtained at the AERONET Kyiv (50.364°N, 30.497°E) and Sevastopol (44.616°N, 33.517°E) stations before and after the passage of the cyclone. At the Sevastopol station, the values of aerosol optical thickness obtained using the SPM photometer are as follows: for May 10, the AOD (500) = 0.09; for May 12, the AOD (500) = 0.1; for May 13, the average daily AOD (500) = 0.08, the minimum for the entire period from May 9 to May 13 AOD (500) = 0.03. Such low values are explained by the fact that from May 11 to May 13 it periodically rained over Sevastopol. The AOD values for the *Kyiv* station at 500 nm wavelength are not available for May 9–31, therefore, the analysis of the aerosol optical characteristics for this station was undertaken based on the data obtained at 675 nm wavelength (AOD (675)). On May 12, the AOD values are very low (AOD (675) = 0.024), since the third stage of cyclone development (maximum development) has already passed by this day and almost all the aerosol was washed out of the atmosphere by precipitation. For May 13 at the Kyiv station, AOD (675) = 0.416, which is 2.5 times higher than the monthly average one for May 2021 (AOD (675) = 0.165), since smoke aerosol was also observed over the station on that day.

After the passage of the cyclone, the smoke exposure could also occur at the Russian stations AERONET Moscow_MSU_MO (55.707°N, 37.522°E), Zvenigorod (55.695°N, 36.775°E), and the station Minsk (53.920°N, 27.601°E) located in Belarus. However, before and during the cyclone, as can be seen on satellite images, the Minsk station was located at a distance from the smoke plume, and on May 12, 13, and 14, clouds were registered at all three stations, so no data on the optical characteristics of atmospheric aerosol is available.

The variability dynamics of the AOD values obtained using AERONET photometers and MODIS satellite data are similar (Fig. 3). However, the data on the AOD variability obtained by remote methods exceed the full-scale values several times, which is confirmed in previous studies [20, 21]. The reflectivity of water and land varies greatly, which causes difficulties in determining optical characteristics using the same algorithms and methods for different types of underlying surface. This leads to the fact that an inaccuracy in the estimation of reflectivity by a value of 0.01 may lead to an inaccuracy in the estimation of AOD by a value of 0.1 [22].

As can be seen from Fig. 3, the smoke cloud on May 10 contains a large concentration of aerosol particles, which are partially buried as a result of the formed cyclone, while most of them spread along the periphery (May 11 and 12), and then they are carried by air currents up to the Gulf of Finland (May 13) (Fig. 1, *a*).

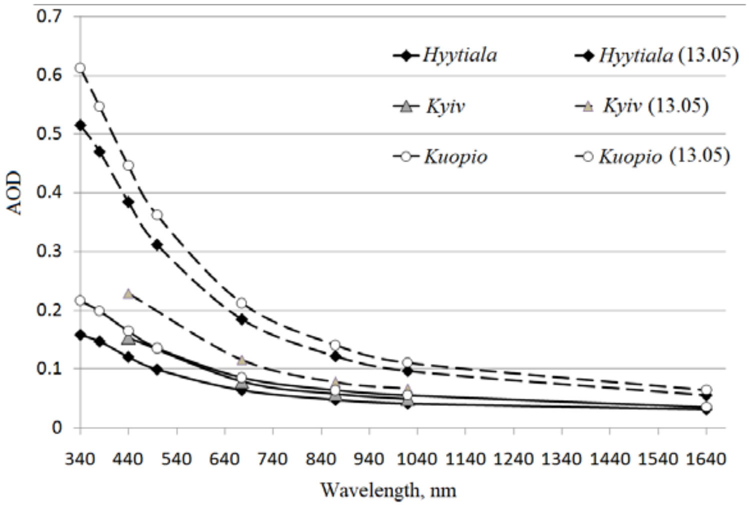


a *b* *c* *d*

F i g. 3. Distribution of aerosol optical thickness according to the MODIS data for May, 10 (*a*), May, 11 (*b*), May, 12 (*c*), May, 13 (*d*), 2021 (https://worldview.earthdata.nasa.gov)

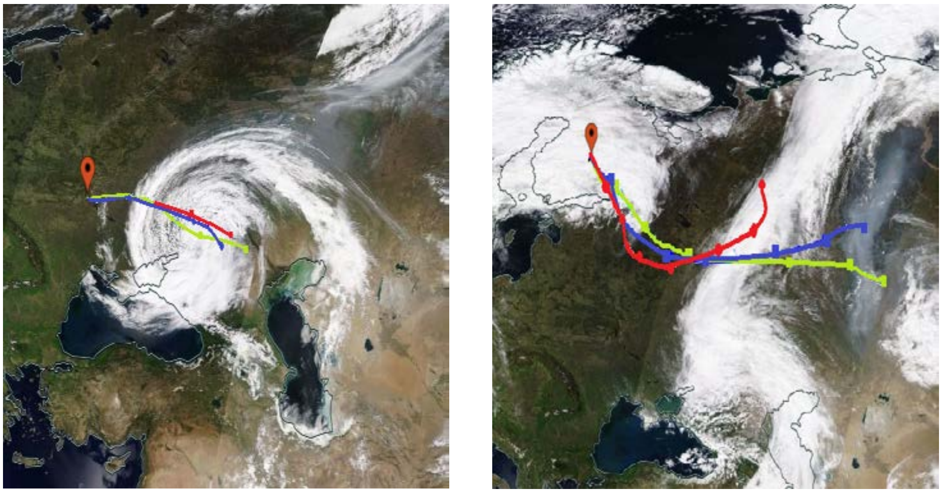
Figure 4 shows the contribution of the coarse and fine fractions to the overall distribution of the AOD at 500 nm wavelength for three stations. As can be seen from the figure, during the registration of smoke aerosol transfer (at the Yekaterinburg station on May 10, 2021 and at the Kuopio and Hyytiala stations on May 13, 2021), an increase in the AOD values was noticeable, and precisely due to the fine fraction.

According to the data from [19], for the two selected sub-arrays of the "smoke/background" data, the most significant changes in the AOD during the smokes occur in the visible range of the spectrum due to high values of the fine component. For instance, in the 500 nm region, the average and modal values of AOD (500) increase by 2.7 times, and the fine-dispersed mode contribution increases by three times. The coarse component also increases in smoke conditions – on average by 1.5 times. Analysis of the data obtained for Hyytiala, Kuopio, and Kyiv stations during the days of smoke registration also showed an increase in the fine-dispersed mode by 1.5–3 times (Fig. 4).



F i g. 4. Spectral variability of AOD for the AERONET station Hyytiala, Kyiv and Kuopio

To confirm the extent of the smoke aerosol distribution, the data of HYSPLIT model, which provides reverse trajectories of air flow movement towards the AERONET stations, respectively, for each day of transfer (Fig. 5), was analyzed. Fig. 5 demonstrates the result of modeling reverse trajectories at heights of 250, 500, and 1500 m for the stations: 1) Kyiv for May 13, where the south-easterly transfer is visible at all altitudes through the area dominated by the cyclone on May 11 (Fig. 5, *a*); 2) Kuopio, where there is an easterly transfer from the Urals (the result of modeling five days before the day of registration of smoke over Finland) (Fig. 5, *b*).

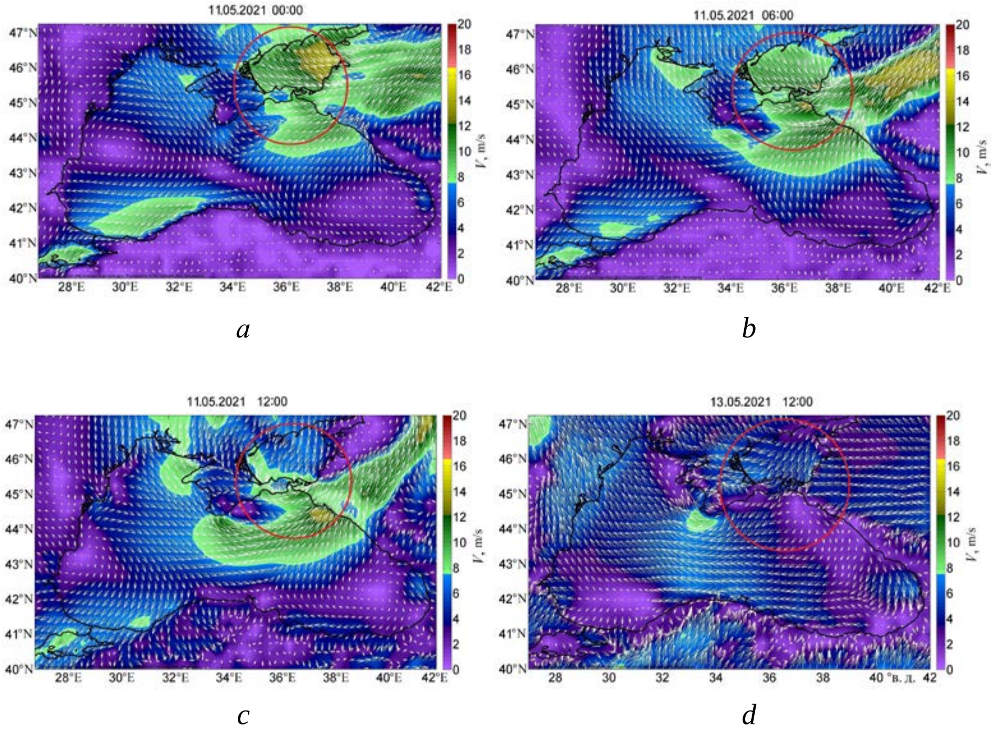


a *b*

Fig. 5. Back trajectories of the air mass transfer based on the results of the HYSPLIT modeling for May 13, 2021 for the AERONET stations Kyiv (*a*) and Kuopio (*b*)

The appearance and development of the cyclone coincide with the beginning of intensive warming of the surface layer, which could affect the variability of the hydrophysical characteristics of the Black Seawaters. To assess the magnitude of the cyclone impact, the surface wind velocities before and during the passage of the cyclone, as well as the spatial distribution of temperature fields and chlorophyll *a* concentration for the Black Sea region, were analyzed.

On the night of May 10–11, the maximum wind impact (its area is marked by a red circle in Fig. 6) was observed in the eastern part of the Sea of Azov (wind velocity *V* reached 14 m/s), in the eastern waters of the Black Sea wind velocity reached 8 m/s (Fig. 6, *a*).

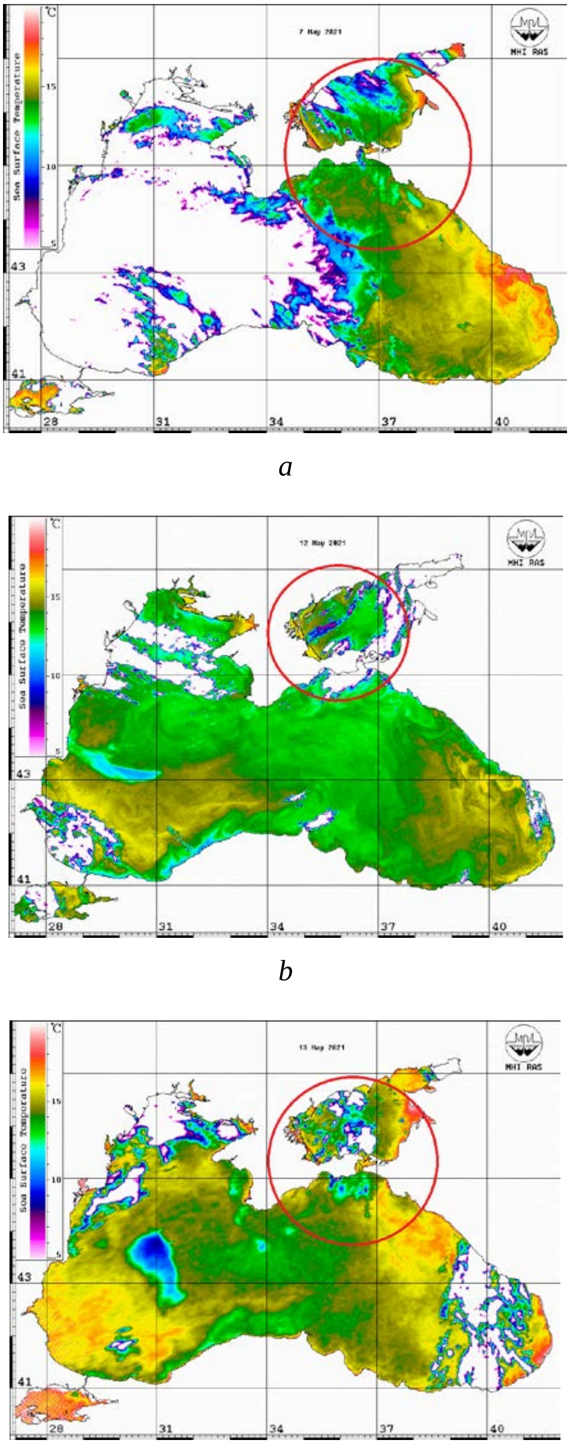


a *b*

c *d*

Fig. 6. Spatial distribution of the surface wind directions and velocities over the Black Sea region on May 11, 00:00 (*a*); May 11, 6:00 (*b*); May 11, 12:00 (c) and May 13, 12:00 (*d*)

On May 11, at 6:00, local wind velocity maximum ($V \approx 15$ m/s) is observed near the Kerch Strait, which shifts to the south during the day (Fig. 6, *b*, *c*). By the end of the day, the wind impact of the cyclone is minimized, and by noon on May 13, in the eastern part of the Black Sea (Fig. 6, *d*) a lull is observed. The variability of wind intensity and direction during the cyclone passage and after it affected the spatial distribution of temperature fields, especially in the zone of maximum velocities.



a

b

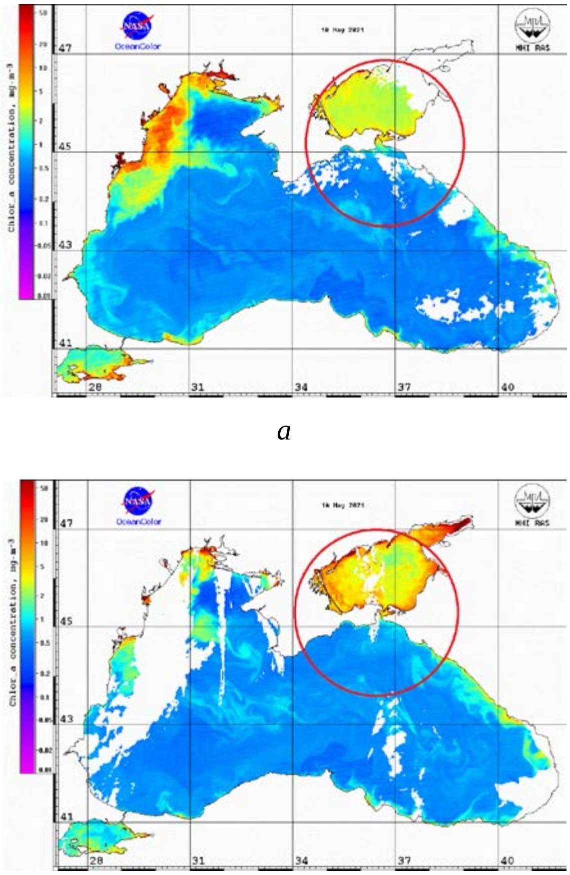
c

Fig. 7. Spatial distribution of surface temperature for the Black Sea region on May, 7 (*a*); May, 12 (*b*) and May, 13 (*c*) based on the VIIRS satellite data

As can be seen from Fig. 7, *a*, even before the passage of the cyclone (May 7) in the eastern part of the Black Sea, a warming of the waters characteristic of the beginning of May (t_{av} = 15°C) was observed.

After the passage of the cyclone (May 12), a temperature decrease in the north-eastern region by 2–3°C (Fig. 7, *b*) is observed. However, from May 13, daytime warming of surface waters is resumed again (Fig. 7, *c*).

An assessment of chlorophyll *a* concentration spatial variability in the zone of the maximum wind impact for the Black Sea region showed minimal differences in concentration values before and after the passage of the cyclone (Fig. 8).

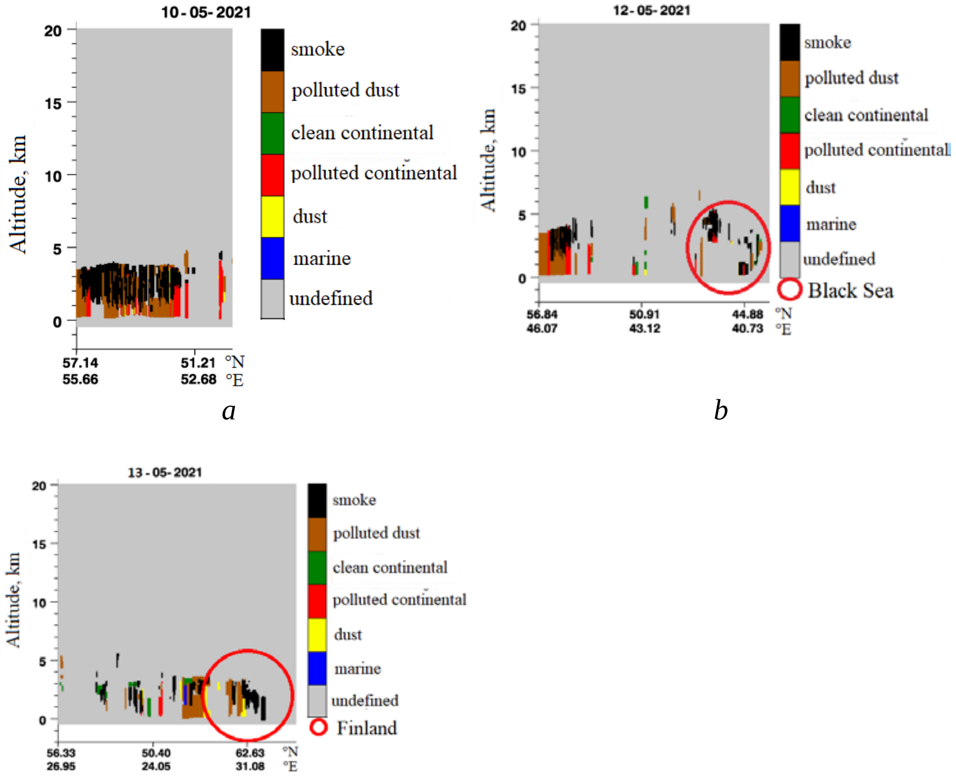


a

b

Fig. 8. Spatial distribution of the chlorophyll *a* concentration over the Black Sea region on May, 10 (*a*); May, 14 (*b*) based on the VIIRS satellite data

Analysis of CALIPSO satellite data on aerosol typing for May 10 over the territory of the Ural (Sverdlovsk Region) confirmed the presence of smoke particles from fires in a surface atmospheric column up to 5 km high (Fig. 9, *a*), on May 12, a smoke aerosol was registered over the Black Sea territory (Fig. 9, *b*), which confirms the spatial distribution of this type of aerosol along the periphery of the cyclone. Since a cloud of smoke was recorded over the Finnish Gulf and Finland according to satellite data, an analysis of aerosol types according to CALIPSO data for May 13 was carried out for the territory closest to the AERONET Kuopio and Hyytial stations. As can be seen from Fig. 9, *c*, a smoke aerosol was registered over the territory of Finland on May 13.



a *b*

c

Fig. 9. Aerosol typing over the Urals on May, 10 (*a*), the Black Sea on May, 12 (*b*), and Finland on May, 13 (*c*) based on the CALIPSO satellite data

There exists a number of factors contributing to the global transfer and distribution of smoke aerosol:

1) multiple intense fires recorded in Western Siberia near the border with Kazakhstan;

2) change of the surface wind direction from western to eastern one on May 9, 2021 over the area of intense fires;

3) accumulation of smoke in the stagnation area located over Sverdlovsk Region;

4) simultaneous formation of a cyclone shifting to the southwest and an anticyclone shifting to the northeast on May 10, 2021.

Conclusion

The fires in the Urals are registered throughout the year, but special fire activity is observed in the spring and summer periods. From May 8 to May 11, 2021, multiple intense fires were registered near the territory of Western Siberia and the border with Kazakhstan. The smoke aerosol formed as a result of biomass combustion is finely dispersed, therefore it can be transported thousands of kilometers from the origin zone under favorable meteorological conditions.

On May 10, an easterly wind prevailed in the lower part of the troposphere, and the combustion products began to distribute to the Urals, and then continued to move along the western periphery of the anticyclone along the Ural ridge to the north. One of the factors due to which the aerosol can move over considerable distances are cyclonic and anticyclonic eddies, which were registered on May 11, 2021. The cyclone formed over the territory of Volgograd Region created favorable conditions, due to which the smoke aerosol was transferred from the site of fires registered in Western Siberia, towards the Black Sea, and subsequently towards the territory of Finland.

According to VIIRS satellite data, the surface water temperature (warming observed since the beginning of May) decreased by 2–3 °C after the cyclone passage in the area of intense wind action. The spatial variability of chlorophyll *a* distribution was not affected by the cyclone.

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