Variability of near-surface aerosol composition in Moscow in the spring of 2020

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Abstract. The paper studies variability in mass concentration and elemental composition of near-surface aerosol in Moscow in March-April 2020. During the study period, noticeable fluctuations in concentration of surface aerosol caused by atypical synoptic and meteorological conditions were revealed. Sharp increase in PM$_{10}$ particle concentration (March 25-29, April 13) is associated with anticyclonic activity and advection of air containing combustion aerosols from the areas with biomass fires. In April as a whole, anomalously low values of aerosol particle concentrations were recorded in comparison with the long-term average. The prevailing dry Arctic air masses significantly decreased the atmospheric aerosol pollution. The decrease of anthropogenic load during COVID-19 non-proliferation actions affected on daily variations of the surface aerosol, smoothing out its typical daily maximal concentration values. Results of spring experiment at the IAP RAS showed good agreement with the data of the Obuchi nearest station of State Budgetary Institution "Mosecomonitoring". We analyzed geochemical spectrum of chemical elements in aerosol and its variability under different synoptic and weather conditions in Moscow. Possible sources and sinks of aerosols are discussed taking into account both abnormal weather conditions and decreased anthropogenic load during a lockdown period in the spring of 2020.

1. Introduction
Increased influence of anthropogenic aerosol pollution on chemical composition and optical parameters of atmosphere is important in modeling the climatic effects of atmospheric aerosol and in assessing and predicting the ecosystem state. The spatial-temporal variability of aerosol characteristics is determined by processes of generation, transformation and sinks of aerosol, gas-chemical transformations in the atmosphere, its turbulence, circulation, as well as interaction with the underlying surface [1-3]. Conditions of large industrial metropolis (dense buildings, sealed urban soils, a special wind regime, influence of the "heat island", as well as the presence of numerous local anthropogenic sources) determine specific features and variability of physicochemical properties of near-surface aerosol. Therefore, study of short-period, seasonal and interannual variations of surface aerosol parameters in large cities, taking into account the above factors, is of great interest.

The most significant variability of aerosols, due to their strong dependence on local and regional sources, as well as on long-range transport, is manifested in spring, during unstable transition period of synoptic and meteorological phenomena. The spring of 2020 in the Moscow metropolis, in a series of long-term observations, was characterized by unique conditions, including those associated with a decrease in anthropogenic load during the lockdown caused by COVID-19 pandemic. The first results
for Moscow [4,5] and for foreign large cities [6-11] showed improvement of air quality in industrial centers during lockdown, with decreased traffic and activity in industry and economy.

This work studies variations in the microphysical parameters and elemental composition of surface aerosol in Moscow in the spring of 2020, during implementation of measures to prevent the spread of coronavirus infection, taking into account the synoptic and meteorological conditions.

2. Subjects, methods, and tools of experimental studies

The objects of research were submicron and micron aerosol particles in the surface layer of the Moscow atmosphere in spring from March 25 to May 3, 2020. The mass concentration of aerosol particles of sizes smaller than 10 μm (PM$_{10}$) and 2.5 μm (PM$_{2.5}$) is calculated daily by a numerical method [2] using microparticle number concentrations measured in a continuous automatic regime with the aid of both LAS-P laser and OEAS-05 optical-electrical aerosol spectrometers (with a time resolution of 5 min) developed at the Karpov Institute of Physical Chemistry [12]. These instruments are installed in the courtyard of the IAP located in the Center of Moscow. The observation site is in the vicinity of motorways with medium and light traffic loads, but away from industrial and power enterprises. The main local pollution sources are associated with motor transport. The IAP courtyard is small and is also used as a parking place for up to ten personal vehicles. It is separated from city streets by a fence and auxiliary brick low-rise buildings, which may decrease the emissions of large aerosol particles from the underlying surface due to transport activity.

The atmospheric composition is intensively monitored for 1–1.5 months in each season of a year, when the mass concentration of total aerosol precipitated onto an AFA-type filter with the aid of aspiration samplers for 24 h (from 9:00 to 9:00 next day) is additionally measured using the gravimetrical method. Within the periods of intensive monitoring, aerosol samples are continuously taken onto hydrophobic filters made of the Petryanov cloth and AFA-WP-10 analytical filters with the aid of a six-cascade impactor. These samples are used to study the mean size distribution of aerosol particles and chemical elements contained in them also using both gravimetrical and inductively coupled plasma mass spectrometry methods. Aerosol samples for both gravimetrical and chemical analyses are taken at a height of 2 m above the land surface.

To assess the influence of meteorological and synoptic conditions on the variability of surface aerosol characteristics, we used data on meteorological parameters obtained with a time interval of 3 hours at the Balchug station located 800 meters North-East of the IAP RAS observation point, as well as from open Internet sources [15]. The analysis of synoptic and meteorological conditions of observations was carried out using Internet resources [16,17] and using the method of backward trajectories of air masses calculated by the NOAA HYSPLIT model [18,19] on the website of the NOAA ARL Air Resources Laboratory [20]. The fire situation in the European Territory of Russia (ETR) and in neighboring countries was also taken into account on the basis of the fire maps of SCANEX Group [21].

The data on the mass concentration of submicron and micron particles obtained at the IAP RAS were compared with the results of observations on the ground network of stations of the State Budgetary Institution "Mosecomonitoring" (MEM). For this purpose, a detailed analysis of the variability of the mass concentration of aerosol particles PM$_{2.5}$ and PM$_{10}$ was carried out at the IAP RAS and at the Spiridonovka station of MEM [22] located in the Central Administrative District of Moscow, northwest from of the IAP RAS, at a distance of about 3 km. This is the MEM station nearest in geographic location and urban conditions (building density, traffic intensity, localization of anthropogenic sources) to the IAP RAS observation point.

When analyzing the possible advection of air containing smoke aerosol from the areas with biomass combustion to the Moscow region, we analyzed the concentration fields of black carbon and dust particles, calculated by MERRA-2 reanalysis (The Modern-Era Retrospective Analysis for Research and Applications, version 2) [17,23-25] on the basis of satellite data.

3. Meteorological conditions

Meteorological parameters were analyzed for March and April 2020 and were compared with the same time period for 2007-2019. Figure 1 on the left shows the temporal variability of daily mean values of meteorological parameters (air temperature, atmospheric pressure and relative air humidity) in 2019,
2020 and their averaged time course for 2007-2020, obtained from the data for station Balchug. The picture on the right shows the wind rose in March and April 2019 and 2020 (Fig. 1). As can be seen from Figure 1, the spring of 2020 was characterized by atypical meteorological and synoptic conditions differing from long-term averages. It should be noted that the warm and snowless winter period of 2020 affected the subsequent spring months as well. March 2020 turned out to be one of the warmest over the past 15 years of observations, and its average monthly temperature exceeded the climatic norm by 6 °C.

![Figure 1. Meteorological conditions in March and April in Moscow: on the left – the time variations in daily averaged temperature, atmospheric pressure and relative humidity (RMS values for means are as vertical dispersion); on the right – wind roses for March and April 2019 and 2020.](image)

April 2020 in Moscow is characterized by anomalies due to two major factors: unfavorable meteorological conditions and lockdown because of the COVID-19 pandemic. April 2020 in Moscow was the coldest over a long-term observation period (see Fig. 1), which was due to the prevalence of the Arctic air masses entering the Moscow region from western, northwestern, and northern directions, and carrying clean air. This is confirmed by results of the analysis of 3-day backward trajectories of air masses, calculated for heights of 100, 250 and 500 m. The wind rose (see Fig. 1 on the right) shows that in April 2020, the western and west-north-west wind directions were predominant.

The second unique phenomenon in April was suspension of vigorous activity of enterprises and institutions, and introduction of mandatory self-isolation of the population of the Moscow region, which led to a significant decrease in anthropogenic load of the metropolis and contributed to purification of the atmosphere from aerosol pollution. On March, 30, a mandatory self-isolation regime was introduced, the activities of most institutions and enterprises were suspended, or a remote mode of operation was
established. On April, 13, stricter measures were taken with the introduction of access control. These measures have significantly reduced the activity of local urban sources, including car traffic. The quarantine was cancelled on June 9, 2020.

In general, the presence of unfavorable weather conditions in March-April 2020 in Moscow, coupled with restrictive measures for the non-proliferation of COVID-19, influenced variability of parameters of surface aerosol.

4. Results

4.1. Time variability of the mass concentration of surface aerosols $PM_{10}$

Figure 2 shows the daily mean values of mass concentration of aerosol particles $PM_{10}$ in the surface atmosphere of Moscow in March and April. The data were obtained from observations at IAP RAS in 2020 and at Spiridonovka (MEM) in 2019, 2020 and the mean values through 2007-2020. The results at both stations in the spring of 2020 correlate very well with each other: the Pearson pairwise correlation coefficients were 0.978 and 0.980 in March and April 2020, respectively. This indirectly confirms the similarity of urban conditions for these two observation points and made it possible to conduct a qualitative study of long-term variability of mass concentration of $PM_{10}$ particles according to the data of previously performed long-term studies at Spiridonovka (MEM).

![Figure 2](image-url)  
**Figure 2.** Temporal variability of daily mean mass concentration of surface aerosols $PM_{10}$ in Moscow according to observations at IAP RAS (2020) and st. Spiridonovka MEM (2019, 2020). For comparison, the graph of daily $PM_{10}$ averaged concentration at st. Spiridonovka MEM (black curve with statistical dispersion ± RMS) for 2007-2019 is also shown.

As can be seen from Figure 2, the time curve of daily mass $PM_{10}$ concentration in 2020 differs greatly from both 2019’s and (2007-2019)’s ones. The differences were most pronounced in April, due to specifics meteorological conditions discussed above. During the intensive experiment at IAP RAS, two anomalous bursts were observed in aerosol $PM_{10}$ mass concentration in 2020: during 5 days – on March 25-29 (when the average daily concentration of $PM_{10}$ exceeded the daily average MPC = 60 μg/m$^3$) and on April 13, 2020. Strong aerosol air pollution in Moscow during these periods is associated with the regional transport of combustion aerosols by air masses NW, W, SW, S, SE directions from areas with numerous of biomass combustion spots (Figure 3). The distributions of black carbon concentration over
the EPR during these days confirms that fires are the main sources of smoke aerosols (Fig. 3, right column).

**Figure 3.** Illustration of fire situation on EPR and the trajectories of long-range air mass transport to Moscow (black dotted lines) during some days of anomalous increase of aerosol PM$_{10}$ concentration in Moscow in March-April 2020. From top to bottom – fire maps according to the data of Scanex service [21] on March 26, 28 and April 13, 2020; the right column – the fields of black carbon near-surface concentration for the same days, obtained from MERRA-2 [17] reanalysis data.

When analyzing anomalous bursts of surface aerosol concentration (Fig. 2), the episode of March 25-29 was conditionally divided into two: March 25-27 and March 28-29. This is associated with the difference in synoptic conditions: in the first case, advection of air containing combustion aerosols occurred with air masses of W-NW directions (regional transfer from Pskov, Tver and Moscow regions), in the second - with air masses of SE-directions (from Ryazan, Tula, Moscow regions). The third episode, April 13, 2020, is associated with the regional transport of combustion aerosols with air masses southwestward (from Kaluga, Smolensk, Bryansk, Kursk, Tula, and Moscow regions and North-West Belarus). These three episodes were characterized by similar synoptic and meteorological conditions: anticyclonic activity, high temperature and low relative humidity. Long-term air advection at the end of March 2020 was mentioned above. On April 13, a short-term invasion of the southern anticyclone was observed between the prolonged dominance of dry Arctic air masses, which clean and cool the air.

During intensive experiment at IAP RAS in Moscow region, lockdown was announced due to the COVID-19 pandemic. This led to reduce in anthropogenic load, mainly associated with decrease in traffic of personal automobile transport and decline in the activity of construction and industrial enterprises, catering and various institutions. In addition, regular washing and disinfection of roads,
streets and courtyards of the metropolis began. These measures led to decrease in aerosol pollution of surface air in Moscow and smooth daytime peaks in diurnal variation of the concentration of aerosol particles. However, analysis of short-period variations in surface aerosol is beyond the scope of this work and is the subject of our further studies.

An indirect factor that makes it possible to assess the influence of urban vehicles on the concentration of aerosol particles in surface layer of the atmosphere of Moscow is the so-called Yandex self-isolation indices (SII – from Yandex service [26]) reflecting business activity in the city. The absolute values of the calculated pairwise Pearson correlation coefficients between the daily mean values of the aerosol mass concentration \( \text{PM}_{10} \) and SII in Moscow were: in April 0.186 (with IAP RAS data), 0.195 (with Spiridonovka MEM data); in May – 0.419 and 0.418, respectively. The obtained values do not allow us to make a conclusion about the significance and suitability of this indicator yet.

In addition, it should be noted that under abnormal weather conditions in April 2020, which significantly influenced the parameters of the surface aerosol in Moscow, it is rather difficult to identify the contribution of anthropogenic load decrease into cleaning the city atmosphere.

### 4.2. Elemental composition of surface aerosols

Information on the elemental composition of aerosol particles is extremely important, since it can indirectly show the local and remote sources of atmospheric pollution [28]. During the intensive experiment at IAP RAS in the spring of 2020, aerosol samples were taken for elemental analysis every day. In total, 65 chemical elements (from Li to U) were determined in the samples. For visual presentation of results, 25 elements are considered, conventionally divided into groups depending on their origin and degree of distribution [14, 27].

To determine the origin of the element (terrigenous or anthropogenic), enrichment coefficients were calculated in relation to the composition of the Earth's crust [14] (the reference element of terrigenous origin is La, data on the average composition of the Earth's crust are taken from [28]). Enrichment factor of the element \( EF_{el} \) is calculated from the concentrations \( C \) for the element and La as follows: \( EF_{el} = (C_{el}/C_{La})_{\text{sample}}/(C_{el}/C_{La})_{\text{Earth crust}} \). In urban aerosol elements with \( EF > 10 \) are usually classified as anthropogenic (not terrigenous). Figure 4 at the top shows the geochemical spectrum of mass concentration of selected elements contained in Moscow surface aerosol and their EFs. So, the elements W, Sn, Cu, Mo, Bi, Sb, Zn, S, Pb, Cd, Se do not have terrigenous origin. There are anthropogenic elements (Sn, Pb, Cd, etc.) and elements of widespread distribution (for example, S, Se). The others are of previously terrigenous origin.

The elemental composition of aerosol can give us possibility to differ the composition of aerosols coming from different regions or from different sources in the city. We combined the samples collected in the days with winds of NW and N directions, when air was come from the Arctic. These days, as a rule, were characterized by low air temperature, lack of precipitation and low concentrations of aerosol particles. The mean element composition for these samples was preliminarily called “suggested background composition” or simply BG. Further, for mass concentration of each element, the excess value relative to BG was calculated as follows:

\[
\text{Exc}_{el} = (C_{el} - BG_{el})/BG_{el}.
\]

Figure 4 at the bottom shows three profiles of elements in relative values to BG for three anomalous episodes associated with regional transport of combustion aerosols (see Fig. 3). Note, that along with combustion aerosols due to convective transfer and advection, particles of mineral origin also entered the surface layer of Moscow atmosphere, which led to increase in concentration of larger, micron-sized aerosol particles in Moscow air. These profiles of elemental concentrations differ significantly both for terrigenous elements (Al, Na, K, Mg, Fe, Ca, La, etc.) and for anthropogenic elements (S, Cr, Mn, Ni, Cu, Zn, Cd, Sn, etc.). This is due to a number of factors, main of which is the difference between anthropogenic sources and sources of biomass combustion, structure and properties of underlying surface (soils and ground). The most variable are heavy metals, including anthropogenic elements in Moscow. The variability of soil elements mainly depends on properties of underlying surface.
Figure 4. Geochemical spectra of elements in surface aerosol of Moscow: top – element concentrations and enrichment factors averaged over all spring 2020 period of observation; bottom – excess (Exc) of elemental mass concentrations relative to BG level for three samples under regional atmospheric transport of combustion aerosols.

However, for detailed classification and deeper study of possible sources of aerosols transported to Moscow with air masses of various origins, we must take into account the dispersed composition and morphology of aerosol particles, physicochemical properties and structure of soil and vegetation cover in regions surrounding the Moscow metropolis, as well as the classification of large regional anthropogenic sources of aerosol emissions.

5. Conclusions
During the spring intensive observations in 2020, two episodes were detected (March 25-29, April 13) associated with strong increase in mass concentration of aerosol particles PM$_{10}$ (including excess of the average daily MPC). These episodes were mainly due to synoptic processes and meteorological conditions. Anticyclonic activity was accompanied by advection of air masses containing combustion aerosols and mineral particles from the areas with multiple biomass fires. The results of elemental analysis of aerosol particles composition confirm this assumption. Significant variability of geochemical profiles of aerosol chemical elements in the samples obtained under various weather and synoptic conditions was revealed.
The rest days of the observation period, lower mass concentration of near-surface aerosols was recorded in comparison with the averaged one. This was significantly influenced by unfavorable meteorological conditions in April, 2020 in Moscow (dominance of dry Arctic air masses with low temperatures). A certain contribution to reduction of aerosol pollution in Moscow during the lockdown was made by decrease in anthropogenic load. The measures for non-proliferation of COVID-19 (decrease in vehicle traffic, decline in the activity of industrial enterprises, regular washing and disinfection of city streets) helped to smooth out the daily high concentration of PM$_{10}$ particles in a typical daily cycle. However, the study of short-term variations in Moscow surface aerosol connected with restrictive measures for non-proliferation of COVID-19 needs more reliable information about them and further research.

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