Environmental Problems

Impact of Restrictive Measures during the Covid-19 Pandemic on Aerosol Pollution of the Atmosphere of the Moscow Megalopolis

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Abstract—The COVID-19 pandemic has led to self-isolation and business interruptions around the world. On the basis of measurements of concentrations of an indicator of aerosol emissions from fuel combustion products—black carbon—it is shown that the decrease in economic activity had a significant effect on the pollution of the Moscow atmosphere. The decrease in the intensity of the traffic and the change in the operating mode of industrial and heat-and-power enterprises of the city during the period of restrictive measures in the spring of 2020 were determined by the dynamics of the daily and weekly trend of black carbon levels. The decrease in the fraction of fossil fuel combustion at this time correlates with the increased contribution of biomass combustion in the residential sector and during agricultural fires around the megalopolis. Changes in the intensity and direction of sources of high concentrations of black carbon were observed during the recovery of economic activity in the summer of 2020. The decrease in the concentration of black carbon and fine particles less than 2.5 μm in size (PM_{2.5}) in the urban atmosphere reflects a decline in economic activity and an improvement in air quality and conditions for maintaining the health of the Moscow population during the COVID-19 pandemic.

Keywords: COVID-19, Moscow, self-isolation, restrictive measures, traffic, air pollution, air quality, concentration of black carbon, PM_{2.5} and PM₁₀.

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In the second half of the 20th century, a response to economic growth around the world was an increase in the concentration of pollutants in the atmosphere [1] and, as a result, an increase in environmental damage [2]. The contribution of human economic activity to this process, including emissions from vehicles, heat power engineering, and industrial facilities, has already exceeded the contribution of natural sources—fires and dust storms.

Pollution of the urban atmosphere. At present, air quality is determined by mass concentrations of the most dangerous gaseous pollutants CO, NO₂, O₃, SO₂, and fine particles less than 10 μm in size

(PM₁₀).¹ The chemical composition of PM₁₀ is determined by anthropogenic and natural sources. Particular attention is paid to the smallest respirable fraction of aerosols less than 2.5 μm in size (PM_{2.5}), which are formed in emissions of primary sources (transport, industry, construction, road dust, fires) and those formed in the atmosphere as a result of photochemical reactions of gaseous emissions of SO₂ and NO₂ from thermal power plants and internal combustion engines. High PM_{2.5} concentrations cause toxic effects on the human body, exacerbation of asthma, lung cancer, and cardiopulmonary diseases [3, 4]. In this context, the World Health Organization (WHO) and environmental protection agencies in different countries have introduced maximum permissible concentrations for the average annual and daily content of PM₁₀ and PM_{2.5} in the air (Table 1). The most polluted are megalopolises with a PM_{2.5} level exceeding 89 $\mu\text{g}/\text{m}^3$, and the cleanest, with an annual average PM_{2.5} value of less than 10 $\mu\text{g}/\text{m}^3$ [5].

¹ PM stands for particulate matter.

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Table 1. Air quality standards and MPCs ($\mu\text{g}/\text{m}^3$) adopted by the WHO, the US Environmental Protection Agency (EPA), the European Union (EU), and the Russian Federation

	Period	WHO	EPA	EU	RF*
PM _{2.5}	Annual average	10	12	25	25
	Daily	25	35		25
PM ₁₀	Annual average	20	—	40	40
	Daily	50	150	50	60

* Hygienic standards GN 2.1.6.3492-17 “Maximum Permissible Concentrations (MPC) of Pollutants in the Air of Urban and Rural Settlements.”

Black carbon (BC) is a product of incomplete combustion of fossil fuels in transport engines, thermal power plants, and biomass in the residential sector, as well as the fumes of agricultural and forest fires. It is formed as agglomerates 100–200 nm in size, consisting of nanoparticles with a diameter of 20–50 nm (Fig. 1a). Global anthropogenic black carbon emissions are estimated at about 7.2 Tg (teragrams) per year and amount to ~15% of the mass concentration of PM_{2.5}; for the transport sector, this value reaches 50% [6]. The anthropogenic influence of the city is identified by the characteristic daily trend of black carbon, which reflects the variability of the intensity of emissions of combustion products in accordance with the operating mode of enterprises and transport [7]. In the process of fuel combustion, a unique structure of graphite microcrystallites is formed (Fig. 1b), due to which black carbon remains the only component of aerosols that absorbs solar radiation well and determines the radiation balance of the atmosphere and climate.

Black carbon is the most dangerous and toxic component of PM_{2.5} from the point of view of the impact of emissions of combustion products on public health in comparison with other sources. In large cities, the risk of chronic and respiratory diseases increases owing to the high degree of air pollution with black carbon from the exhaust of automobile engines [8]. Emissions of burnt fossil fuel are the most significant environmental threat to children’s health worldwide [9]. Due to a number of characteristic properties, black carbon is today considered one of the most important indicators of the impact on human health and the environment [8]. Its mass concentration is accepted by the world environmental protection agencies as a characteristic of continuous monitoring of the degree of aerosol pollution of the atmosphere [10].

Moscow is one of the largest megacities in the world with a high population density and a developed transport, heat and power, and industrial infrastructure that uses natural fuels (gas, diesel, gasoline), which is accompanied by large volumes of aerosol emissions into the atmosphere. The capital has about 630 industrial enterprises registered in various branches of machine building and metalworking, energy, chemistry and petrochemistry, light and food industries, and construction. About 50% of pollutants are emitted by enterprises that produce and redistribute energy, gas, and water. Industrial production zones occupy about 17% of the city’s area; the 14 largest enterprises provide up to 85% of gross pollution from stationary sources [11]. The total volume of industrial emissions is dominated by processing plants and electricity distribution enterprises; gas accounts for 96.7% of fuel consumption. A central heating system operates in Moscow, and biomass is not used for heating, in contrast to large cities in China and Europe [12, 13]. The combustion of biomass is believed to contribute a small share to the pollution of a city’s atmosphere.

Fig. 1. Structure of black carbon microparticles: agglomerates in the emission of (a) a diesel engine of automobile transport [33] and (b) the internal structure of graphite microcrystallites [35].

Fig. 2. COVID-19 cases recorded in Moscow from April to August 2020.

In 2019, the average annual concentrations of PM10 and transport emissions in the capital amounted to 0.8 MPC (see Table 1) and up to 93% of gross pollution [14]. Analysis of the dynamics of the main pollutants that determined air quality in 2005–2014 showed that Moscow is comparable in this indicator with European cities [15]. However, the Russian Federation has not yet adopted a method for monitoring combustion products in the atmosphere; there are no MPC standards for black carbon. Its mass concentrations are only measured for scientific purposes [16, 17]. In August 2010, during extreme pollution by smoke emissions from fires around the Moscow metropolis, abnormally high concentrations of PM10 and black carbon were recorded, 34 times higher than the MPC according to EU standards (see Table 1) and seven times the MPC level in a normal period [18].

The state of the environment during the pandemic. The COVID-19 pandemic, announced by WHO on March 11, 2019, has had a significant impact on public health and economic activity around the world. Many countries introduced a self-isolation regime and a number of measures limiting economic activity and traffic. It has become clear that the impact of the pandemic is an unprecedented experiment in quantifying the impact of collective responses on the environment, including urban air quality. Analysis of data on global air quality showed a significant decrease in the concentrations of oxides NO_2 and CO , which dominate the emissions of internal combustion engines of road transport, compared to the level of 2019 [19]. European cities recorded a decrease in CO_2 emissions from 8 to 75% (<https://www.icos-cp.eu/event/933>) and NO_2 down to 62% [20]. A decrease in atmospheric concentrations of primary pollutants (NO_x , CO , SO_2 , volatile organic components) led to a change in the ozone concentrations of secondary organic aerosols, depending on the meteorological conditions of the region [21]. It was assumed that the decline in eco-

nomic activity would lead to a significant reduction in PM2.5 in the aerosol load of the atmosphere. However, measurements carried out in the largest cities of the world showed different levels of the decrease in the mass concentrations of PM2.5, from the maximum, by 35% [20], to the absence of any changes [22], owing to the ambiguous dependence of transformation processes occurring in the emissions of primary sources into the atmosphere.

Black carbon, as a direct product of fuel combustion, has become one of the most significant indicators of the impact of changes in transport intensity and industrial production on the environment during the pandemic. According to the observations of 17 European stations, the emission of black carbon in Europe dropped by 11% compared to the same period in previous years [23]. Significant temporal changes in the concentration of black carbon occurred in the countries that introduced the most stringent restrictive measures. In large cities, its average concentration during quarantine dropped by 35–47% compared to the period before the epidemic [24, 25]. The decrease in the concentration of indicators of primary vehicle emissions—the number of fine particles and black carbon, registered on roads of different traffic intensity classes—reached 60–68% and 22–46%, respectively [26]. The highest emission of black carbon was observed in the spring of 2020 in the residential sector of cities due to the intensive combustion of biomass at low air temperatures [23].

In Moscow, the number of reported cases of COVID-19 increased from April to June 2020, but by the end of summer the situation had stabilized (https://www.rospotrebnadzor.ru/region/korono_virus/epid.php) (Fig. 2). Restrictive measures during the pandemic influenced the intensity of the economic activity of the metropolis. The quarantine lasted from March 26 to May 12, after which some enterprises received permits to work. On June 1, Mos-

Fig. 3. Collection and analysis of data on aerosol load of the atmosphere during the COVID-2019 pandemic.

cow began to ease strict restrictions on movement and work of the population. On June 1, the period of restrictive measures ended, and the recovery period began. By June 18, business activity returned to its former course, and by the end of the summer life in the city returned to normal. Estimates of changes in the concentration of the gaseous pollutants CO, NO₂, NO, and PM10, according to Mosecomonitoring data, are recorded in [27], which presents the results of the analysis of aerosol pollution of the atmosphere of the Moscow megalopolis during the COVID-19 pandemic based on measurements of the most important indicators of hazardous impact on the environment and human health—black carbon and the mass concentration of PM2.5. The influence of the decline in economic activity and the intensity of the traffic flow during the period of restrictive measures in spring 2020 and the subsequent increase in activity during the recovery period in the summer of 2020 on the change in the mass concentration of black carbon, its daily and weekly trend, and the direction of sources of high concentrations is shown.

Technique for measurement of aerosol contamination. The aerosol load in the atmosphere and meteorological parameters were measured in the southwestern part of Moscow, at the Meteorological Observatory of Moscow State University, located far from large enter-

prises and highways, which means that it can characterize the conditionally background state of the urban environment. The main stages of data collection and analysis are shown in Fig. 3. The mass concentration of PM10 was determined using a TSI OPC optical particle counter after calibration with a TEOM 1405 (Thermo Fisher Scientific, United States). The respirable fraction of particles less than 2.5 µm in size (PM2.5) and the dust fraction of the largest particles ranging in size from 2.5 to 10 µm (PM2.5–10) were estimated. The optical properties of aerosols were measured using an AE33 aethalometer (Magee Scientific, United States) at seven wavelengths in the range from ultraviolet to infrared. The mass concentration of black carbon was determined from the change in the attenuation of radiation at a wavelength of 880 nm. By the difference in spectral absorption of emissions from high-temperature combustion of fossil fuel (FF) in engines and low-temperature biomass burning (BB), depending on the wavelength, the contribution determined by the percentage of FF% and BB% was estimated based on the model [28]. The black carbon concentration data and wind directions as a pollution rose made it possible to identify the location of local sources of maximum BC concentrations. The regional distribution of biomass burning sources (fires) around the Moscow megalopolis was determined by the ratio

Fig. 4. Average mass concentrations of black carbon (BC), the share of combustion of biomass BB% and natural fuel FF%; average mass concentrations of PM2.5, PM2.5–10, and PM10 during the period of restrictive measures and during the recovery period. Percentage changes over the recovery period are shown in relation to the period of restrictive measures.

of the calculated trajectories of air mass transfer for the entire period to the black carbon concentration at the time of their arrival at the observation point [29]. An array of reverse trajectories of air mass transfer with a

step of 48 hours back at an altitude of 500 m, obtained on the basis of the HYSPLYT model and archived meteorological data from GDAS, was used for the calculations (<http://www.arl.noaa.gov/ready>).

Table 2. Mean and root-mean-square errors of the mass concentration of black carbon (BC), PM10, PM2.5, and PM2.5–10, the share of fossil fuel combustion FF%, biomass BB%, and meteorological parameters during the period of restrictive measures and during the recovery period. Meteorological parameters: temperature (T), wind speed (WS), and precipitation

Characteristic	Period of restrictive measures	Recovery period
BC and PRM		
BC, $\mu\text{g}/\text{m}^3$	0.9 ± 0.7	1.6 ± 1.4
PM2.5, $\mu\text{g}/\text{m}^3$	3.5 ± 2.7	5.1 ± 3.0
PM2.5–10, $\mu\text{g}/\text{m}^3$	12.4 ± 8.1	11.2 ± 7.0
PM10, $\mu\text{g}/\text{m}^3$	16 ± 10	16.3 ± 9.3
Fraction of fuel and biomass burned		
FF%	79.5 ± 9.9	86.8 ± 3.8
BB%	20.5 ± 9.9	13.2 ± 3.8
Meteorological parameters		
T , deg	8.3 ± 4.6	18.5 ± 3.5
WS, m/s	2.0 ± 0.8	1.7 ± 0.6
Precipitation, mm	4.3 ± 7.0	3.9 ± 8

Changes in the mass concentration of black carbon during the pandemic. During the period of restrictive measures, low values of black carbon were observed: on average $0.95 \pm 0.7 \mu\text{g}/\text{m}^3$ (Table 2), the minimum was $\sim 48 \text{ ng}/\text{m}^3$. During the recovery period, its concentration increased significantly and amounted to $1.6 \pm 1.4 \mu\text{g}/\text{m}^3$, the maximum values reaching $\sim 13.6 \mu\text{g}/\text{m}^3$. Changes in the mean concentrations during these intervals are shown in Fig. 4. During the transition from one period to the other, there was a significant increase in the mean concentration of black carbon, which was 75% due to the resumption of transport and economic activity in Moscow. During the restrictive measures after May 12, when a number of enterprises received work permits, the average concentration of black carbon increased by 22%. These numbers matched well with TomTom's traffic statistics (https://www.tomtom.com/en_gb/traffic-index/moscow-traffic). In Moscow, during the period of restrictions (April 15–June 1, 2020), the average daily level of road congestion ranged from 2 to 20%, and during the period of economic recovery (June 1–August 31, 2020), it increased on weekdays to 36–72% and on weekends to 40–45%.

During the transition from the period of restrictive measures to the recovery period, the percentage of fossil fuel combustion (FF%) increased from 79 to 87% (see Fig. 4), which indicated an increase in its con-

Fig. 5. (a) Daily and (b) weekly variations in the mass concentration of black carbon (BC) and the fraction of combustion of biomass BB% during the period of restrictive measures (PRM) and during the period of recovery (PR).

sumption with the restoration of traffic intensity and the work of the energy and industrial sectors. The black carbon component from biomass combustion is not directly related to economic activity. It shows the opposite trend: a high percentage of biomass burning ($\sim 20\%$) was observed precisely during the period of restrictive measures (see Fig. 4). Since biomass is not used in the Moscow heating system, the sources of its combustion should be sought in emissions from incineration plants and among emissions from waste and wood burning in the residential sector of Moscow oblast. During the most stringent self-isolation, a significant part of Muscovites were forced to move out of town and live in dachas in Moscow oblast, where biomass is widely burned for heating houses and garbage disposal. The period of restrictions included the holidays of May 1 and 9, during which a particularly high proportion of the population lived outside the city.

Since the COVID-19 epidemic coincided with the spring season of agricultural activity around Moscow, plumes of smoke from fires may have contributed to the aerosol composition of the urban environment, as was established in the spring of 2017 [30]. During the period of restoration of economic activity of the population from June 1, there was a decrease in the fraction of biomass burning on average to 13%; later this value did not change. Apparently, this level corresponds to the pollution of Moscow's urban environ-

ment by emissions from biomass burning in the summer season.

Impact of restrictive measures on the change in the daily and weekly trend of black carbon concentrations. The daily variation in aerosol concentrations depends on the height of the atmospheric boundary layer, which is determined by the processes of heating, mixing, and photochemical activity, as well as the variability of emissions from sources. During the restrictive measures in Moscow, the daily BC variation differed significantly from the recovery period by lower hourly averaged values and flat dynamics with the absence of a morning maximum (Fig. 5). Such a diurnal variation was formed due to the low traffic intensity and moderate economic activity of the city, in contrast to the typical course for large cities in the spring–summer time, when the maximum concentration of black carbon is observed in the morning hours due to the increase in the traffic intensity and the maximum energy load [7, 31]. At night, its level rose to $1.4 \mu\text{g}/\text{m}^3$, similar to that measured by employees of the Meteorological Observatory of Moscow State University in the spring of 2017–2018 [30]. Since diesel engine exhaust contains much more black carbon than gasoline-fueled engines, its high level at night is the result of the peculiarities of the regulation of cargo transportation in Moscow, where the entry of heavy vehicles into the city center is limited during the day. A similar diurnal variation with high nighttime concentrations is

Fig. 6. (a) Pollution roses with black carbon (BC) and the share of combustion of biomass BB% during the period of restrictive measures (PRM) and during the period of recovery (PR); (b) the locations of the industrial zones and facilities of the fuel and energy sector (HPPs, heating stations (HSs), and boiler houses), oil refineries, and waste incineration plants closest to the Moscow Observatory (MO) of Moscow State University (MSU).

observed in cities with a regulated flow of cargo transport, which is allowed to travel only at night [32]. During the recovery of economic activity, a significant increase in the black carbon concentrations was observed at any time of the day, as was a change in the shape of the diurnal cycle. The recovery of economic activity has led to a consistently high level of pollution by emissions from fuel combustion products at night and in the morning, which is typical of an urbanized environment.

During the period of restrictive measures, the nature of the diurnal variation for the fraction of biomass burning was distinguished by a long daily maximum (see Fig. 5), which in spring with an average air temperature of about 8° (see Table 2) corresponded to the economic activity of the population in intensive waste burning and heating country houses. In summer, during the recovery period, the average daily temperature increased to 18° , the percentage of biomass burning fell, and the diurnal variation leveled off.

The weekly variation of the black carbon concentration during the restrictions shows the lowest level in the middle of the week and its increase by the weekend (see Fig. 5), as could be expected in the situation of long nonworking days during the period of significant restrictions on the working activity of the urban population. The recovery in economic activity changed the weekly trend of black carbon: its high concentrations shifted to working days, which is typical of the normal life of the city. The flat weekly BC trend during the

recovery period is typical of the summer vacations of a significant part of the population, when there is practically no difference in emissions from transport and enterprises between working days and weekends.

Changes in the direction of sources of high concentrations of black carbon during the pandemic. The roses of black carbon pollution show that during the restrictive measures its concentration rarely exceeded $3 \mu\text{g}/\text{m}^3$; until May 7, sources of high concentrations—more than $4 \mu\text{g}/\text{m}^3$ —were located 4 km to the southwest of the Moscow State University Meteorological Observatory—the Ochakovo industrial zone and the largest HPP-25 (Fig. 6). After the central heating was turned off, the direction of the highest recorded concentrations changed to the northwest—from the side of the Fili industrial zone. During the recovery period, the concentration of black carbon increased to $5\text{--}6 \mu\text{g}/\text{m}^3$ towards the source in the southwest from the Ochakovo industrial zone, as well as in the southeast, where the facilities of HPP-20 and ABZ PK Virazh, Moscow's asphalt and concrete company, are located closest to the observatory.

During the period of restrictive measures, the maximum value of the fraction of biomass burning ($\sim 20\%$) was recorded in the directions of the northeasterly and northwesterly winds (see Fig. 6). A potential source could be Moscow's largest waste incineration Special Plant No. 2, located in the industrial zone of the Northwestern Administrative Okrug, which processes up to 160 000 t of waste per year. Other sources associ-

Fig. 7. Regional distribution of the share of BB% of biomass combustion (fires) around Moscow during (a) the period of restrictive measures and (b) the recovery period.

ated with the transfer of air masses from Moscow oblast with dense residential development of settlements and summer cottages, where wood is widely used for heating houses and is burned during garbage disposal, could have made a large contribution.

In April–May around Moscow, smoke emissions from agricultural fires make a significant contribution to the aerosol load on the atmosphere [34]. In 2020, during this period, satellite data of anomalous thermal glow showed high fire activity in the Moscow region. Figure 7 shows the regional distribution of biomass burning sources (fires) around Moscow, which determine the BB% during the restrictive measures and in the recovery period. The highest concentrations of smoke emission sources were found in the north of Moscow. During the recovery period, which lasted all summer, the maximum BB% did not exceed 14%; no significant sources of biomass combustion were observed (see Fig. 7). At that time, according to satellite data, forest fires were recorded only south of Moscow.

Changes in the mass PM concentration during the pandemic. Analysis of the daily variation of the mass concentration of PM_{2.5}, carried out by the staff of the Meteorological Observatory of Moscow State University from 2011 to 2013, indicates common anthropogenic sources of the most dangerous gaseous atmospheric pollutants and primary aerosols [34]. The values of the mass concentrations of PM₁₀ were 1.5–2 times higher than those of PM_{2.5}, which was determined by a significant contribution to the total mass of the coarse dust fraction and soil particles in the range from 2.5 to 10 μm (PM_{2.5}–10). During the period of strict restrictions until June 1, 2020, the Meteorological Observatory recorded a low value of the mass concentration of PM_{2.5}, on average $3.5 \pm 1.7 \mu\text{g}/\text{m}^3$ (see Table 2), which increased by 43% in the recovery period (see Fig. 4). The growth of air pollution by fine

particles with the recovery of economic activity indicated a deterioration in air quality in the megalopolis. The same trend was observed during the recovery of industrial production and the activity of road transport in Moscow after the crisis of 2008–2009 [34]. The fraction of black carbon in PM_{2.5} during the restrictions was $33 \pm 2\%$; there was no noticeable change in the ratio of BC to PM_{2.5} during the recovery period.

The dynamics of changes in the mass concentration of the larger dust fraction PM_{2.5}–10 during the pandemic turned out to be opposite to PM_{2.5} (see Table 2). Its increase during the restrictions demonstrated the most significant aerosol pollution of the atmosphere for the spring period from the underlying surface after the melting of the snow cover and the beginning of the process of soil dusting. From June 1 to 18, during the maximum precipitation that reached 7.5 mm (see Table 1), the lowest concentration of PM_{2.5}–10 was observed—on average $7.8 \pm 4.2 \mu\text{g}/\text{m}^3$ —as a result of the washing out of large particles from the atmosphere with rain.

During the period of strict restrictions until June 1, 2020, the average mass concentration of PM₁₀ was at the level of $16 \pm 10 \mu\text{g}/\text{m}^3$; no changes were recorded during the recovery period. It can be concluded that the mass concentration of PM₁₀ is the least identifiable of changes in the economic activity of the city population.

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During the COVID-19 pandemic in the spring of 2020, the introduction of strict measures of restrictions and self-isolation led to an improvement in the ecological state of the atmosphere in Moscow compared to the subsequent summer period. Black carbon in the emissions from the combustion of fuels used by transport and city enterprises turned out to be an

effective indicator of reducing the aerosol load of the atmosphere and the emission of hazardous toxic substances into the atmosphere. The decrease in the flow of vehicles led to low values of the concentration of black carbon and a flat dynamics of its daily variation due to the reduced energy load in the morning hours. The change in the operating mode of enterprises affected the redistribution of emission intensities from working days to weekends. The fraction of biomass burning exceeded the summer level of normal life in the region due to increased emissions of waste and wood burning in the residential sector of Moscow oblast and seasonal agricultural fires. During the period of recovery of economic activity in the summer of 2020, the intensity increased and the direction of sources of high concentrations of black carbon from large industrial zones and HPP enterprises changed. The mass concentration of PM_{2.5} in the respirable aerosol fraction increased significantly, about 30% of which was the most dangerous and toxic component—black carbon. Experimental study of short-term changes in the state of the atmosphere during a rapid extreme fall and subsequent recovery of economic activity makes it possible to understand better the processes taking place in the economy—society—environment system of large cities.

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