Impact of COVID-19 Pandemic Preventing Measures and Meteorological Conditions on the Atmospheric Air Composition in Moscow in 2020

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Abstract—Changes in the atmospheric composition during different periods of 2020 in Moscow which were associated with the COVID-19 pandemic preventing measures as well as corresponding pollutant emission reduction, are investigated. Surface concentrations of nitrogen dioxide (NO$_2$), carbon monoxide (CO), ozone (O$_3$), aerosol fraction (PM$_{10}$), and meteorological parameters during different periods of 2020 were compared with similar data for the previous five years. The analysis of ground-based measurements, as well as of high-resolution satellite distributions of CO and NO$_2$ indicated that the concentration of major pollutants and its spatial distribution in the Moscow region were significantly affected by both restrictive measures and abnormal meteorological conditions in 2020.

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1. INTRODUCTION

The pollution of atmospheric air is among the urgent problems facing humanity. According to scientists, every eighth death is associated with it [16]. Therefore, the struggle for the air quality improvement, especially in big cities, where the problem is the most acute, is an integral part of the “green” agenda that is gaining momentum around the world. A key instrument in this struggle is the reduction of anthropogenic emissions of pollutants to the atmosphere.

An essential reduction of emissions of polluting gases and aerosols to the atmosphere was caused by the restrictive measures introduced by official authorities of different countries during the COVID-19 pandemic in 2020. In the cities on different continents, a significant decrease in the traffic activity, economy, and population mobility was registered. This caused a decrease in emissions and surface concentrations of pollutants, especially of nitrogen oxides [6, 15] and, to a lesser degree, sulfur dioxide, carbon monoxide, and particulate matter [9, 21]. With the detailed inventory of pollution sources and the rather branched network of observations of the atmospheric composition, the chemical transport modeling using reduction factors for emissions from different economic sectors made it possible to estimate the contribution of COVID-19 preventing measures to the air quality improvement in different cities in Europe [13].

It was more difficult to assess the effect of restrictive measures in Moscow for two reasons. Firstly, at the lockdown peak in the spring of 2020, meteorological conditions in Moscow were abnormal and favored a rapid dispersion of pollutants, leveling the impact of emission reduction [2]. The exclusiveness of meteorological conditions makes it not quite correct to compare the concentrations of pollutants in the spring of 2020, which were expectedly low [1, 4], with similar periods for other years and neighboring periods in 2020. Secondly, an insufficient detailing of emissions in the Moscow region still does not allow a full use
of high-resolution (1–2 km) chemical transport modeling [3]. Hence, the application of the approach described in [13] to Moscow gives quite rough results.

Obviously, in this situation, a more detailed analysis using all available information is needed. Let us try to analyze the situation using observations of meteorological parameters and the atmospheric composition not only in the surface atmospheric layer but also in the boundary one, as well as using high-resolution satellite data.

2. METHODS

Six stations with the most complete measurement dataset (>90%) uniformly distributed over the megacity were selected from the dataset of the Mosekomonitoring air quality monitoring network (Fig. 1). Measurements at the stations are conducted using modern gas analyzers, which are regularly calibrated according to international standards and instructions of the World Meteorological Organization (WMO) developed for the Global Atmospheric Watch (WMO GAW) observation network [18].

Meteorological observations at VDNKh station (2-m wind speed, temperature, and amount of precipitation for every 3 hours) and radiosonde observations (the launches at 03:00 and 15:00 Moscow time (MSK)) in Dolgoprudny (the northern suburb of Moscow, station ID 27713, data and method descriptions are available at http://weather.uwyo.edu/upperair/sounding.html) were used for analyzing meteorological conditions in the atmospheric boundary layer (ABL). Raw data are the set of profiles of meteorological parameters (humidity, temperature, wind speed, wind direction, etc.) in the layer from the surface to the altitude of 20–30 km. To obtain wind speed profiles with a step of 100 m in the ABL, raw data were interpolated by the polynomial function of degree three with a step of 1 m for all available altitudes. The one-dimensional function interp1 incorporated to the MATLAB R2016b was used to interpolate the data:

\[ A2(xx) = \text{interp1}(x, A1(x), xx, \text{"cubic"}) \]

where A1 is initial measurement data; A2 is interpolated data; x is the altitudes of initial measurements; xx is specified interpolation altitudes with a step of 1 m from the surface to 10 km.
Then, discrete levels with a step of 100 m were selected from the resulting profile of high-resolution data, using which average wind speed in the layer of 100–500 m from the ground was calculated.

Satellite data of the TROPOMI mission launched in 2017 were additionally used for revealing the features of variations in the total concentration of nitrogen dioxide NO$_2$ and carbon monoxide CO in the atmospheric column. The Level 2 OFFL data (the OFFL processing level, i.e., archival data that passed primary filtering) on the concentration of NO$_2$ and CO available since the second half of 2018 (https://sentinels.copernicus.eu/web/sentinel/data-products) were used as initial data. Thus, the Level 2 for a user is the primary level that contains 15 Net CDE files for one measurement day for every pollutant (according to the number of satellite orbits per day) with a spatial resolution at nadir of 7’7 km until the middle of 2019 and 5.5’3.5 km from the middle of 2019 [7, 11]. The Level 3 (L3) TROPOMI NO$_2$ OFFL and TROPOMI CO OFFL data (data converted into one daily file) are absent, therefore, each research team “produces” TROPOMI L3 on its own. The tropomi_tools special software was developed to analyze TROPOMI data. It allows performing the collection of TROPOMI L2 data, their subsequent conversion into L3 (uniting 15 Net CDE files into a single daily .mat file with preserving an initial resolution and location of primary pixels). In addition, based on the Level 3 data of several orbital spectrometers (MODIS/Terra/Aqua, AIRS/Aqua, and TROPOMI/Sentinel-5P), the software can calculate and map spatial distributions of concentrations of several pollutants for an arbitrary domain with a specified spatial resolution (as a rule, it is in the range from 0.1° to 1.0° for TROPOMI), with an option of obtaining distributions, both separate daily ones and averaged for arbitrary days. To analyze the fields of total CO and tropospheric NO$_2$ in different periods of 2019 and 2020, the resolution of 0.5° was used, which provided the clearest visualization of the results. The aforementioned software was used in [5] to analyze the distributions of total CO obtained using the AIRS spectrometer.

To reduce the impact of atmospheric transport on the concentration and spatial distribution of pollutants when comparing data for 2019 and 2020, the days with quasi-calm conditions in the ABL were selected. Observations from VDNKh station (average 2-m wind speed for standard measurements with 3-hour intervals, totally 8 values per day) were used for sampling. By analogy with [5], the sample included the days when the sum of wind speeds for all measurements with 3-hour intervals did not exceed 5 m/s, i.e., for such approach, average daily wind speed did not exceed 5 m/s: 8 measurements = 0.625 m/s. For minimizing the effect of short-term variability during the analysis of atmospheric composition changes in the period of restrictive measures, long time periods were distinguished in 2020 in accordance with the intensity of the restrictions (Table 1). Data on the atmospheric composition and meteorological parameters for the similar periods in 2015–2019 from all the above stations were prepared for comparison with 2020. Such approach was applied to analyze changes in the atmospheric composition, which were associated with the pandemic preventing measures in 2020 in different cities of the world [20]. The periods recommended in [20] for the European cities almost coincide with the periods of similar activities held in Moscow.

3. RESULTS AND DISCUSSION

The comparison of averaged meteorological characteristics for the time periods distinguished according to Table 1 shows (Fig. 2) that almost during the whole analyzed period, wind speed in the ABL in 2020 considerably exceeded average wind speed in 2015–2019 (Figs. 2a and 2b). This difference is especially noticeable at night (Fig. 2b). The temperature regime during the period of lockdown corresponds to the minima over the similar periods in 2015–2019 (Fig. 2c), and the amount of precipitation during the full

| Period | Start | End | Number of days | Note |
|--------|-------|-----|----------------|------|
| I      | Before lockdown | February 8 | March 9 | 30 | No restrictions |
| II     | Partial lockdown | March 10 | March 29 | 19 | Partial travel restrictions |
| III    | Complete lockdown | March 30 | June 8 | 70 | Maximum restrictions |
| IV     | Partial relaxation of lockdown | June 9 | September 24 | 107 | Partial removal of restrictions on the traffic and enterprise operations |

Table 1. The time periods in 2020 in accordance with the intensity of COVID-19 preventing measures in Moscow
lockdown significantly exceeds the typical values for the preceding years (Fig. 2d). It is obvious that such deviations of meteorological parameters could not but affect the atmospheric composition.

The comparison of average concentrations of major atmospheric pollutants (CO, NO$_2$, O$_3$, and PM$_{10}$) for the time periods corresponding to different intensities of restrictive measures in 2020 with similar data for 2015–2019, which was performed for several stations in different parts of Moscow, is presented in Table 2. It confirms the supposition about the effect of meteorological anomalies on the surface atmospheric composition in Moscow in 2020.

For example, almost for all selected stations except Novokosino, the concentration of CO during the complete lockdown is minimal as compared to five preceding years (Table 2). The concentration of another major pollutant, NO$_2$, for most stations (except Novokosino and Cheremushki) during the complete lockdown is also much lower than in the other years. The concentration of PM$_{10}$ during the period of maximum restrictions is noticeably low for all stations and is minimal (except for Cheremushki) as compared with the previous years.

The changes in the atmospheric composition in 2020 are more clearly observed in Fig. 3, which presents weekly concentrations of major pollutants (CO, NO$_2$, O$_3$, and PM$_{10}$) averaged over the selected Moscow-monitoring stations (taking into account availability of observations for each pollutant). The figure clearly shows that the lockdown period is characterized by the significant decrease in the concentration of all pollutants except ozone in Moscow. Despite the weather during the period of maximum restrictions, which was generally unfavorable for the ozone generation, an increase in surface ozone values was registered in the city at the beginning of the complete lockdown (see Fig. 3c). This growth is probably caused by the shift of the photochemical equilibrium toward the decreasing level of volatile organic compounds against a background of reduced direct emissions from vehicles and the industry. A similar effect was noted by researchers during lockdowns in many other cities across the world [10, 17]. The most significant decrease during the complete lockdown relative to 2015–2019 was found for the concentration of nitrogen oxides (Fig. 3b), and the smaller decrease was revealed for CO (Fig. 3a) and PM$_{10}$ (Fig. 3d). Nitrogen dioxide is a clearly pronounced anthropogenic pollutant with a short lifetime (few hours to few days), it is significantly a result of motor transport operations and is formed as a result of the oxidation of nitrogen oxide NO emitted by motor vehicles. It is not surprising that the decrease in the surface concentration of nitrogen oxides during lockdowns was recorded almost everywhere [1, 8, 12, 19, 20]. The decrease in the total concentration of NO$_2$ over megacities and large urban areas was also registered.
The features of atmospheric composition in the Moscow region against a background of the COVID-19 pandemic can also be observed in the TROPOMI-based distributions of total CO and tropospheric NO$_2$ for the days with the quasi-calm ABL conditions and for different periods in 2019 and 2020 (in accordance to the periods related to the lockdown, see Table 1 and Fig. 4). The sample for the days with quasi-calm conditions was used to exclude the effect of long-range pollutant transport and wind pattern features. Figures 4a, 4b, 4c, and 4d are the visualizations of the difference in the pollutant concentration between the period “before the complete lockdown” and the period of “the complete lockdown,” separately for 2019 and 2020.

For example, for total CO in 2020, the above difference is negative in the entire analyzed domain and is rather large (up to $-2 \times 10^{17}$ molecule/cm$^2$, which makes up ~10% of the background total concentration). This negative difference is rather uniformly distributed across the domain (Fig. 4b).

A quite interesting and, at first glance, unexpected result was obtained for tropospheric NO$_2$. In 2019, regional features of the distribution of the difference in tropospheric NO$_2$ between the period before the complete lockdown and the period of the complete lockdown (Fig. 4c) can hardly be bound to any area, while there is a noticeable NO$_2$ growth in 2020 near the borders of the Moscow oblast during the complete lockdown as compared to the period before the lockdown (Fig. 4d). At the same time, an expected decrease in the level of NO$_2$ was recorded in Moscow and adjoining suburbs (Fig. 4d). In our opinion, this result is explained by the closure of most enterprises in Moscow and by the transfer of a significant number of em-
Fig. 3. The station-averaged (see Table 2 and Fig. 1) weekly concentrations of pollutants in Moscow in (1) 2015–2019 and (2) 2020: (a) CO; (b) NO$_2$; (c) O$_3$; (d) PM$_{10}$. The 7-day (weekly) averaging was chosen to eliminate an effect of weekly emission cycles.

Fig. 4. The difference in (a, b) total CO and (c, d) tropospheric NO$_2$ according to the TROPOMI data (the resolution is 0.5°) for the periods of January 1–March 29 (“before the complete lockdown”) and March 30–June 8 (“complete lockdown”) for (a, c) 2019 and (b, d) 2020. In all cases, the sample for the days with quasi-calm conditions in the atmospheric boundary layer was used.
ployees to distance working, as well as by the mass departure of Moscow residents in the spring and summer of 2020 to country houses. The mentioned circumstances led to the significant decrease in the intensity of traffic (that is the main anthropogenic source of nitrogen oxides) within the city [1] and probably to the increase in anthropogenic activity and traffic flows in suburban areas.

4. CONCLUSIONS

Thus, the presented analysis indicated considerable changes in the atmospheric composition over Moscow in 2020 after the introduction of the set of restrictive measures on the COVID-19 pandemic prevention. However, the decrease in the concentrations of major pollutants during the period of complete lockdown was also significantly associated with abnormal windy and rainy weather. It is impossible to estimate the contribution of the reduction of anthropogenic (mainly transport) emissions to the changes in the atmospheric composition against a background of extreme meteorological conditions. It is generally obvious that the variations induced by reduced emissions during the pandemic did not go beyond synoptic variability as noted in some other studies [9]. The detailed estimates can be obtained using chemical transport modeling if the detailed inventory of anthropogenic emissions is provided.

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REFERENCES

1. A. S. Ginzburg, V. A. Semenov, E. G. Semutnikova, M. A. Aleshina, P. V. Zakharova, and E. A. Lezina, “Impact of COVID-19 Lockdown on Air Quality in Moscow,” Dokl. Akad. Nauk, No. 1, 495 (2020) [Dokl. Earth Sci., No. 1, 495 (2020)].
2. D. P. Gubanova, A. A. Vinogradova, M. A. Iordanskii, and A. I. Skorokhod, “Time Variations in the Composition of Atmospheric Aerosol in Moscow in Spring 2020,” Izv. Akad. Nauk, Fiz. Atmos. Okeana, No. 3, 57 (2021) [Izv., Atmos. Oceanic Phys., No. 3, 57 (2021)].
3. N. A. Ponomarev, N. F. Elansky, A. A. Kirsanov, O. V. Postlyakov, A. N. Borovski, and Y. M. Verevkin, “Application of Atmospheric Chemical Transport Models to Validation of Pollutant Emissions in Moscow,” Optika Atmos. Okeana, No. 2, 33 (2020) [Atmos. Ocean. Opt., No. 4, 33 (2020)].
4. O. B. Popovicheva, M. A. Chichaeva, and N. S. Kasimov, “Impact of Restrictive Measures during the COVID-19 Pandemic on Aerosol Pollution of the Atmosphere of the Moscow Megalopolis,” Vestnik Rossiiskoi Akad. Nauk, No. 4, 91 (2021) [Her. Russ. Acad. Sci., No. 2, 91 (2021)].
5. V. S. Rakitin, N. F. Elansky, A. I. Skorokhod, A. V. Dzhola, A. V. Rakitina, A. V. Shilkin, N. S. Kirillova, and A. V. Kazakov, “Long-term Tendencies of Carbon Monoxide in the Atmosphere of the Moscow Megapolis,” Izv. Akad. Nauk, Fiz. Atmos. Okeana, No. 1, 57 (2021) [Izv., Atmos. Oceanic Phys., No. 1, 57 (2021)].
6. M. D. Adams, “Air Pollution in Ontario, Canada during the COVID-19 State of Emergency,” Sci. Total Environ., 742 (2020).
7. A. Apituley, M. Pedergnana, M. Snee, J. P. Veefkind, D. Loyola, J. Landgraf, and T. Borsdorff, Sentinel-5 Precursor/TROPOMI Level 2 Product User Manual Carbon Monoxide, http://www.tropomi.eu/sites/default/files/files/Sentinel-5P-Level-2-Product-User-Manual-Carbon-Monoxide_v1.00.02_20180613.pdf.
8. J. D. Berman and K. Ebisu, “Changes in U.S. Air Pollution during the COVID-19 Pandemic,” Sci. Total Environ., 739 (2020).
9. A. Briz-Redon, C. Belenguer-Sapina, and A. Serrano-Aroca, “Changes in Air Pollution during COVID-19 Lockdown in Spain: A Multi-city Study,” J. Environ. Sci., 101 (2021).
10. H. Chen, J. Huo, Q. Fu, Y. Duan, H. Xiao, and J. Chen, “Impact of Quarantine Measures on Chemical Compositions of PM2.5 during the COVID-19 Epidemic in Shanghai, China,” Sci. Total Environ., 743 (2020).
11. H. Eskes, J. van Geffen, F. Boersma, K.-U. Eichmann, A. Apituley, M. Pedergnana, M. Sneep, J. P. Veefkind, and D. Loyola, *Sentinel-5 Precursor/TROPOMI Level 2 Product User Manual Nitrogen Dioxide*, https://sentinel.esa.int/documents/247904/2474726/Sentinel-5P-Level-2-Product-User-Manual-Nitrogen-Dioxide.

12. C. Gao, S. Li, M. Liu, F. Zhang, V. Achal, Y. Tu, S. Zhang, and C. Cai, “Impact of the COVID-19 Pandemic on Air Pollution in Chinese Megacities from the Perspective of Traffic Volume and Meteorological Factors,” Sci. Total Environ., 773 (2021).

13. M. Guevara, O. Jorba, A. Soret, H. Petetin, D. Bowdalo, K. Serradell, C. Tena, H. A. C. Denier van der Gon, J. Kuenen, V. Peuch, and C. P. Garcia-Pando, “Time-resolved Emission Reductions for Atmospheric Chemistry Modelling in Europe during the COVID-19 Lockdowns,” Atmos. Chem. Phys., 21 (2021).

14. P. Krecl, A. Creso Targino, G. Yoshikazu, R. P. Cassino Jr., “Drop in Urban Air Pollution from COVID-19 Pandemic: Policy Implications for the Megacity of Sao Paulo,” Environ. Pollut., 265 (2020).

15. Q. Liu, J. T. Harris, L. S. Chiu, D. Sun, P. Houwer, M. Yu, D. Duffy, M. Little, and C. Yang, “Spatiotemporal Impacts of COVID-19 on Air Pollution in California, USA,” Sci. Total Environ., 750 (2021).

16. National Academies of Sciences, Engineering, and Medicine, 2016. *The Future of Atmospheric Chemistry Research: Remembering Yesterday, Understanding Today, Anticipating Tomorrow* (The National Academies Press, Washington, DC).

17. C. Ordonez, J. M. Garrido-Perez, and R. Garcia-Herrera, “Early Spring Near-surface Ozone in Europe during the COVID-19 Shutdown: Meteorological Effects Outweigh Emission Changes,” Sci. Total Environ., 747 (2020).

18. N. A. Ponomarev, V. P. Yushkov, and N. F. Elansky, “Air Pollution in Moscow Megacity: Data Fusion of the Chemical Transport Model and Observational Network,” Atmosphere, 12 (2021).

19. S. Selvam, P. Muthukumar, S. Venkatramanan, P. Roy, K. Manikanda Bharath, and K. Jesuraja, “SARS-CoV-2 Pandemic Lockdown: Effects on Air Quality in the Industrialized Gujarat State of India,” Sci. Total Environ., 737 (2020).

20. R. S. Sokhi, V. Singh, X. Querol, S. Finardi, A. Targino, M. Andrade, R. Pavlovic, R. Garland, J. Massague, S. Kong, A. Baklanov, L. Ren, O. Tarasova, G. Carmichael, V. Peuch, V. Anand, G. Arbilla, K. Badali, G. Beig, L. Belalcazar, A. Bolignano, P. Brimblecombe, P. Camacho, A. Casallas, J. Charland, J. Choi, E. Chouridakis, I. Coll, M. Collins, J. Cyrys, C. D. da Silva, A. D. di Giosa, A. di Leo, C. Ferro, M. Gavidia-Calderon, A. Gayen, A. Ginzburg, F. Godefroy, Y. Gonzalez, M. Guevara-Luna, S. Haque, H. Havenga, D. Herod, U. Horrak, T. Hussein, S. Ibarra, M. Jaimes, M. Kaasik, R. Khairwal, J. Kim, A. Koussa, J. Kukkonen, M. Kulmala, J. Kuula, N. la Violette, G. Lanzani, X. Liu, S. MacDougall, P. M. Manseau, G. Marchegiani, B. McDonald, S. V. Mishra, L. Molina, D. Mooibroek, S. Mor, N. Moussiopoulos, F. Murena, J. Niemi, S. Noe, T. Nogueira, M. Norman, J. L. Perez-Camano, T. Petaja, S. Piketh, A. Rathod, K. Reid, A. Retama, O. Rivera, N. Rojas, J. P. Rojas-Quincho, R. San Jose, O. Sanchez, R. Seguel, S. Sillanpaa, Y. Su, N. Tapper, A. Terrazas, H. Timonen, D. Toscano, G. Tsegas, G. Velders, C. Vlachokostas, E. von Schniedemesser, R. Vpm, R. Yadav, R. Zalakeviciute, and M. Zavalas, “A Global Observational Analysis to Understand Changes in Air Quality during Exceptionally Low Anthropogenic Emission Conditions,” Environ. Int., 157 (2021).

21. J. Xiang, E. Austin, T. Gould, T. Larson, J. Shirai, Y. Liu, J. Marshall, and E. Seto, “Impacts of the COVID-19 Responses on Traffic-related Air Pollution in a Northwestern US City,” Sci. Total Environ., 747 (2020).