Modeling Surface Air Pollution with Reduced Emissions during the COVID-19 Pandemic Using CHIMERE and COSMO-ART Chemical Transport Models

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Abstract—The results of numerical modeling of air pollution using CHIMERE and COSMO-ART chemical transport models are presented. The modeling was performed according to the scenarios of the 50–60% reduction of emissions from anthropogenic sources in the Moscow region during the period of March–July 2020. Scenario calculations of pollutant concentrations were compared with baseline simulations using regionally adapted inventory of anthropogenic pollutant emissions to the atmosphere. The most significant decrease in the concentrations of NO\textsubscript{2} and CO was reproduced by the models when emissions from two sectoral sources (vehicles and nonindustrial plants) were reduced. The PM\textsubscript{10} drop was mostly influenced by the reduction of emissions from industrial combustion. With the total reduction of emissions from anthropogenic sources as compared to the baseline calculations, the pollutant concentration decreased by 44–54% for NO\textsubscript{2}, by 38–44% for CO, and by 26–39% for PM\textsubscript{10}. This generally coincides with the quantitative estimates of the pollution level drop obtained by other authors. The greatest effect of reducing pollutant emissions into the atmosphere was found during the episodes of adverse weather conditions for air purification, when the simulated and observed pollution level increases by 3–5 times as compared to the conditions of intense pollutant dispersion.

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INTRODUCTION

The displays and effects of the reduced emission of pollutants during the COVID-19 pandemic have become a subject of close attention of researchers [2, 10, 13, 17, 18, 21, 22, 24, 27, 28, 30, 31]. The pandemic impact has been already discussed in the special issues of open electronic journals, which presented corresponding estimates for many countries (for example, the special issue of Science of the Total Environment (STOTEN) journal [29]). According to observations, the drop of air pollution level as compared to the previous years was recorded during the pandemic in Europe, Asia, and North America. The greatest effect of quarantine measures, the dramatic reduction in traffic flows and industrial production in densely populated agglomerations was manifested in a decrease in the surface concentrations by 40–70% for nitrogen oxides, by 25–30% for carbon monoxide, by 40–50% for PM\textsubscript{10}, and by 13–26% for PM\textsubscript{2.5} [16, 32]. At the same time, some publications [17, 22, 24, 30] noted an increase in surface ozone values by 20–26% (almost by 40% according to [28]) as a result of the change in the balance of gases involved into the photochemical generation of ozone.
The effects of reduced pollutant emissions to the atmosphere in the Moscow region according to observations were considered in [2, 4]: the 30–50% decrease in the concentration of major pollutants was shown for the megalopolis.

The changes in the concentration of anthropogenic pollutants during the lockdown provided researchers with a unique opportunity to verify model simulations of air pollution. Some foreign publications discussed the estimates of emission reduction during the COVID-19 period obtained by modeling using the WRF-Chem [32], CAMSx [25] chemical transport models (CTM), and observational data. The similar estimates for the Moscow region were performed by the authors using the CHIMERE CTM and the COSMO-Ru2-ART system. These models were used as a research tool to perform scenario calculations of NO\(_x\), CO, PM\(_{10}\), and O\(_3\) surface concentrations (NO\(_x\) is nitrogen oxides, PM\(_{10}\) is the mass concentration of fine particulate matter, CO is carbon monoxide, O\(_3\) is ozone) in the megalopolis. The aim was to assess the efficiency of the total reduction of anthropogenic emissions, as well as of the reduced emissions from individual sectoral sources.

**DATA AND METHODS**

In the recent years mesoscale meteorological models and related atmospheric chemistry models have evolved rapidly. Nowadays modeling is being widely used for research and practical purposes [9]. The Hydrometcenter of Russia has developed a technology for the air pollution modeling using the CHIMERE chemical transport model and the COSMO-Ru2-ART system, which belongs to the class of online models simulating atmospheric and chemical processes on the same grid using a single main time step for integration. The CHIMERE belongs to the class of online models with incorporated independent meteorology and chemistry models, which may even have different grids. This modern numerical model is quite well known abroad [11, 13, 14, 19, 22, 26], there is experience of its application for assessing urban planning measures for management decision-making [26], for developing scenarios and performing numerical simulations of pollutant concentrations with reduced emissions from sectoral sources [19]. The CHIMERE version 2013b [22] with a horizontal grid spacing of 0.038°x 0.02° in calculations for the Moscow region is currently configured to assimilate the EMEP (European Monitoring and Evaluation Program) emission data [15]; the outputs of COSMO-Ru2 operational meteorological model with a horizontal resolution of about 0.02° are used for modeling [7].

The COSMO-ART model consists of the COSMO (Consortium for Small-scale Modelling) mesoscale nonhydrostatic meteorological model and ART (Aerosols and Reactive Trace gases) atmospheric chemistry model. The feature of the COSMO-Ru2-ART (unlike the CHIMERE) is the coupled calculation meteorological parameters and chemical transformations at each time step, which allows taking into account an inverse effect of aerosol and gases on radiation processes and meteorological conditions [1]. The COSMO-Ru2-ART utilizes a spherical coordinate system with a shifted pole. The grid points coincide with those of the COSMO-Ru2.2 meteorological model [7], which calculations are used in the COSMO-Ru2-ART as initial and boundary conditions.

Originality of the model experiments consists in using a single source of emission data by the both models, the EMEP open database [15]. Taking into account the experience of foreign researchers in the regional correction of inventory emissions [8], the EMEP inventory data in the model domain were preliminarily adapted to the Moscow region. The spatiotemporal correction of annual emissions presented in the EMEP on the 50 × 50 km grid was performed [3, 8]. The corrected original emissions on the 2-km grid were used for baseline calculations of model pollutant concentrations and for preparing “experimental” reduced sectoral emissions.

The efficiency of the emission reduction was assessed by the levels of pollution with CO, NO\(_x\), PM\(_{10}\), and O\(_3\) by comparing concentrations of the baseline calculation and scenario modeling averaged over the domain covering the Moscow territory. Air pollution monitoring data (https://mosecom.mos.ru/vozdux/) were used to verify model simulations.

**SCENARIOS OF MODEL EXPERIMENTS**

The scenarios with a percentage reduction of emissions were proposed for experimental simulations. The experience of scenario modeling for estimating contributions of individual sources was described, for example, in [19], where the CHIMERE-based experiments with the 50% reduction of emissions from the dwelling heating and motor vehicles in Santiago (Chile) were discussed. The scenario estimates of the emission reduction efficiency during the pandemic were also described in [13, 21].
A free access to the EMEP emission data allows correcting the inventory content. Using the procedure built into the CHIMERE, the data presented on a regular grid (mg/cell per year) are converted to the CTM grid taking into account GlobCover (GlobCover Land Cover) land use types [12]. At the preprocessing stage during the CHIMERE run, the annual number of emissions is distributed across months, days of week, and time of day, i.e., the gridded emission fields are prepared for the desired calculation period. The EMEP data ([15], https://www.eea.europa.eu/ru/publications/rukovodstvo-emep-inventarizacii) are distributed across 11 sectoral sources, SNAPs (Selected Nomenclature for sources of Air Pollution). The contributions of the sectoral sources to the total emission of controlled pollutants presented in Table 1, were calculated for the Moscow region [5, 8]. Taking into account specific features of the sectoral sources in the scenario calculations, it was decided to unite the emissions from the SNAP7 and SNAP8, as well as SNAP2 and SNAP3 sources, which have close characteristics. The estimation of the contribution of emissions from manufacturing plants (SNAP4) and the heat power sector (SNAP1) is of special interest, since according to available official data [2, 4], emissions from the heat power plants during the spring pandemic in Moscow were reduced less significantly than industrial and vehicle emissions.

The results of model estimation are discussed for the prescribed maximum values of the sectoral emission reduction (by 50–60%) in the Moscow region. The conditions of five scenarios are indicated in Table 2. The scenario simulations were carried out by modeling pollutant concentrations with the CHIMERE and COSMO-Ru2-ART CTMs for the period of March–July 2020, which included the time of strict limitations (till the middle of June) and gradual mitigation of restrictive measures.

### MODEL SIMULATIONS

The modeling of pollutant concentrations with the CHIMERE and COSMO-ART CTMs with a horizontal grid spacing of 2.2 km for 24 hours was performed using the forecast data of the COSMO-Ru2.2 meteorological model [7]. The meteorological provision of CTM calculations with forecast data with a small lead time is justified in terms of the conditional approximation to real weather conditions.

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**Table 1.** The distribution (%) of CO, NOx, and PM10 emissions to the atmosphere from SNAP sectoral sources in the EMEP database

| SNAP | Sectoral sources                                      | CO  | NOx | PM10 |
|------|-------------------------------------------------------|-----|-----|------|
| 1    | Combustion in the power industry                      | 1   | 9   | 9    |
| 2    | Nonindustrial combustion plants                       | 6   | 5   | 12   |
| 3    | Combustion in the manufacturing industry             | 13  | 13  | 14   |
| 4    | Production processes                                  | 3   | 2   | 23   |
| 5    | Extraction and distribution of fossil fuels and geothermal energy | 0   | 0   | 1    |
| 6    | Use of solvents                                      | 1   | 0   | 2    |
| 7    | Motor transport                                       | 56  | 45  | 24   |
| 8    | Other mobile sources and mechanisms                   | 13  | 24  | 6    |
| 9    | Waste recycling and disposal                          | 5   | 2   | 7    |
| 10   | Agriculture                                           | 2   | 0   | 2    |

**Table 2.** The scenarios of numerical experiments on the reduction of emissions from sectoral sources

| Scenario | SNAP types                                      | Changeable emission source | Reduction, % |
|----------|-------------------------------------------------|----------------------------|--------------|
| 1        | Motor transport, other mobile sources and mechanisms | SNAP7 + SNAP8 + SNAP4 + SNAP1 + SNAP2 + SNAP3 + SNAP4 + SNAP7 + SNAP8 | 60           |
| 2        | Production processes                             | SNAP4 + SNAP1 + SNAP2 + SNAP3 | 60           |
| 3        | Combustion in the power industry                 | SNAP1 + SNAP2 + SNAP3       | 50           |
| 4        | Combustion at nonindustrial plants and in manufacturing industry | SNAP1 + SNAP2 + SNAP3 + SNAP4 + SNAP7 + SNAP8 | Simultaneously, like in scenarios 1–4 |
| 5        | Total for scenarios 1–4                          | SNAP7 + SNAP8 + SNAP4 + SNAP1 + SNAP2 + SNAP3 + SNAP4 + SNAP7 + SNAP8 | Simultaneously, like in scenarios 1–4 |
Quantitative changes in the monthly mean of the simulated pollutant concentrations in the CTM domain covering the Moscow region were used as an indicator of efficiency of reduced sectoral emissions to the atmosphere. The simulations based on scenario 1 demonstrated that the reduction in the emission from vehicles (SNAP7, SNAP8) by 60% in March–July led to a decrease in the concentration by 29–40% for NO$_2$, by 18–32% for CO, and by 13–18% for particulate matter (Fig. 1).

The pollutant emission to the atmosphere from industrial facilities reduced by 60% (scenario 2) was manifested only in an essential PM$_{10}$ drop: monthly mean PM$_{10}$ decreased by 11–15%, the respective values for NO$_2$ and CO dropped by 1% only. Such results could be caused by the fact that, according to the EMEP inventory, industrial emissions on the territory of Moscow are insignificant due to a small number of industrial facilities in the city.

The experimental CHIMERE run with the emission from heat power plants (SNAP1) reduced by 50% (scenario 3) also showed an insignificant impact of this source to the pollutant concentrations: the city-averaged monthly mean concentrations of CO, PM$_{10}$, and NO$_2$ dropped by less than 1%. An insignificant effect of heat power plants on the surface air pollution in Moscow (on the concentrations of CO, PM$_{10}$, and NO$_2$) revealed by the modeling may be associated with peculiarities of SNAP1 emissions in the EMEP data: unlike the other (ground) sectoral sources, it is high-altitude. It was shown in [4, 10] that 70% of direct emissions is released to the height of 350 to 780 m, and 15% is released to the layer of 180–350 m.

The model simulations with the COSMO-Ru2-ART based on the coupled scenarios 1 and 3 revealed a decrease by 22–23% for CO and by 33–46% for NO. Due to the NO concentration drop, the values of O$_3$ in the city increased by 10–22%. On some days and at some moments, a decrease was registered by 0.03–0.06 mg/m$^3$ for NO and by 0.02–0.03 mg/m$^3$ for surface ozone (Fig. 2).

The CHIMERE-2.2 calculations based on scenario 4 with the emission from industrial combustion processes (SNAP2, SNAP3) reduced by 60% revealed the second most significant (after motor transport) source of air pollution over the city. The strongest response to the SNAP2, SNAP3 reduction was found in the PM$_{10}$ drop (by 11–15%), and the weakest response was found in the CO decline (by 5–8%).
Scenario 5 implied a simultaneous 50–60% reduction of emissions from the most significant sources. Such total reduction of emissions from the sectoral sources provided a decrease in the monthly mean concentrations by 44–54% for NO\textsubscript{2}, by 26–39% for CO, and by 38–44% for PM (Fig. 3).

It should be noted that the results of numerical simulation based on the CTMs with reduced inventory emissions were adequate to the air pollution variations according to observations at the air quality monitoring network in Moscow (https://mosecom.mos.ru). As shown in [2], the pollutant concentrations during the lockdown in Moscow were lower than usual; in the residential areas of the city, the concentrations dropped below the normal by 1.4 times for CO, by 1.8 times for NO\textsubscript{2}, by 2.2 times for NO, by 2.1 times for SO\textsubscript{2}, and by 1.6 times for PM\textsubscript{10}. There is also evidence that the emissions from heat power facilities decreased by 22% as compared to the same period in 2019 (https://mosecom.mos.ru/novosti-i-publikacii/2020/07/moskovskij-vozdux-osnovnye-itogi-pervogo-polugodiya-2020-goda/).

**DISCUSSION OF RESULTS**

When interpreting the results of scenario modeling, it is necessary to take into account that numerical simulations were based on forecast data of the COSMO-Ru2.2 meteorological fields [7]. It should be understood to which extent the simulated meteorological processes were typical of the analyzed period. It is noteworthy that the index of the North Atlantic Oscillation (NAO), one of the major characteristics of the Northern Hemisphere large-scale atmospheric circulation, in the first three months of 2020 was positive, thus indicating the dominance of the zonal circulation [23]. However, in April–July, the NAO was in the negative phase, with the dominance of the meridional circulation.

The reviews [6] show that large-scale atmospheric processes over the European part of Russia in the spring and the first months of the summer of 2020 were accompanied by significant weather anomalies: March in Moscow was almost 6°C warmer than normal, and April and May were 1.5–1.7°C colder. The period of frequent rains started in May and finished in July; the amount of precipitation in May and June was almost three times above the normal; already by August 2020, the annual precipitation normal was reached in Moscow.

The anomalous atmospheric events in the Moscow region should include an increased transport velocity in the lower atmospheric layers as compared to the typical values for the spring-summer period (Fig. 4). In April–June 2020 (strict quarantine) the air mass velocity in the lower layer was on average 1–2 m/s higher than in the preceding 2019, which is an indirect indicator of the activity of the dynamic
mixing in the lower atmosphere and the prevalence of favorable conditions for the dispersion of pollutants present in the atmosphere.

One more illustration of the abnormal atmospheric circulation pattern in the analyzed period is a decrease in so-called “stagnant” situations usually accompanied by the significant surface air pollution. Such adverse weather conditions (AWC) for the pollutant dispersion are determined by the thermal stability and slow transport in the lower atmospheric layers [3]. According to the authors, the AMC frequency in the Moscow region in the spring and summer of 2020 made up 4% and the respective value for the same period in 2019 was 8%.

Particular attention to the AWC is caused by the fact that it favors the most significant air pollution. According to experimental scenario calculations, the maximum effect of reduced emissions was manifested during the AWC episodes. This effect is demonstrated by the model simulations of NO$_2$, PM$_{10}$, and CO concentrations under conditions of the intense pollutant dispersion (March 23–24) and in the AWC episode (March 27–28), which are presented in Fig. 5. In case of the AWC, a three–four-fold increase in the pollu-

![Fig. 5](image_url)
tion level occurs. The same figure illustrates the detected selective response of different pollutants to the reduced emissions from individual sources. For example, the largest decrease in the concentration of NO\textsubscript{2} and CO is simulated by the CTM in case of the reduced emissions from vehicles (SNAP7, SNAP8, scenario 1) and combustion products at production plants (SNAP2, SNAP3, scenario 2) with the maximum pronounced effect of the pollution reduction in the AWC episodes. The PM\textsubscript{10} drop is more strongly affected by the reduced emissions from industrial combustion (SNAP2, SNAP3, scenario 4) than the reduced vehicle emissions (scenario 1).

The numerical experiments are practically significant, their main results and conclusions may be used for developing emission control activities during the AWC. With the AWC warning system existing at Roshydromet, a need to take emission reduction measures is transmitted basically to industrial enterprises. The experimental simulations based on chemical transport models showed that in the cities where the main contribution to the surface air pollution is made by vehicle emissions, the greatest effect on the air quality improvement can be achieved by motor transport emission reduction. The model calculations demonstrated that emissions from heat power plants on average have an insignificant effect on the surface air pollution with nitrogen oxides, carbon monoxide, and particulate matter in Moscow.

CONCLUSIONS

The numerical experiments based on the simulations with the CHIMERE and COSMO-Ru2-ART chemical transport models with the inventory emission variations (EMEP) during the first pandemic wave (March–July 2020) demonstrated the results which generally coincide with the published Russian and foreign data on the pollution level drop in megacities.

The scenario model experiments with the CHIMERE and COSMO-Ru2-ART models with the 50–60% reduction of emissions from sectoral sources to the atmosphere showed a concentration decrease by 44–54% for NO\textsubscript{2}, by 38–44% for CO, and by 26–39% for PM\textsubscript{10}. The modeling revealed that the greatest contribution to the decrease in NO\textsubscript{2} and CO is made by the vehicle emission reduction and the PM\textsubscript{10} drop is largely determined by the reduction of emissions associated with the combustion processes at plants. An important result of the numerical experiments with the emission variations is a revealed effect of the insignificant impact of heat power plants on the total surface air pollution in Moscow.

Favorable weather conditions for the pollutant dispersion prevailed in the Moscow region during the period of quarantine measures, which in combination with restrictive activities provided a dramatic decrease in the air pollution level in Moscow. The number of AWC episodes was twice smaller than in the previous year, which to a certain extent could have masked an effect of the real reduction of emissions to the atmosphere from industrial enterprises and vehicles.

The results of the experimental modeling of pollution dynamics with reduced anthropogenic emissions during the pandemic may be a reason for revising current understanding and traditional methods of environmental prediction.

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