atmosphere

MDPI

Article

Evaluation of the Impact of COVID-19 Restrictions on Air Pollution in Russia's Largest Cities

Anna Morozova [1,2,*], Oleg Sizov [1], Pavel Elagin [3], Natalia Lobzhanidze [1], Anatoly Fedash [1] and Marina Mironova [1]

[1] Faculty of Petroleum Geology and Geophysics, Gubkin Russian State University of Oil and Gas, 119991 Moscow, Russia; kabanin@yandex.ru (O.S.); burgasova@yandex.ru (N.L.); fedash.a@gubkin.ru (A.F.); mma.ecology@gmail.com (M.M.)
[2] Center for Resilience and Ecology, Strelka KB, 119072 Moscow, Russia
[3] Institute of Ecology, Peoples' Friendship University of Russia, 117198 Moscow, Russia; fanakapa@gmail.com
* Correspondence: morozova-a.e@yandex.ru; Tel.: +7-9-160-671-852

Abstract: Governments around the world took unprecedented measures, such as social distancing and the minimization of public/industrial activity, in response to the COVID-19 pandemic in 2020. This provided a unique chance to assess the relationships between key air pollutant emissions and track the reductions in these emissions in various countries during the lockdown. This study considers atmospheric air pollution in the 78 largest Russian cities (with populations over 250,000) in March–June of 2019–2021. This is the first such study for the largest cities in Russia. The initial data were the TROPOMI measurements (Sentinel-5P satellite) of such pollutants as carbon monoxide (CO), formaldehyde (HCHO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2), which are the main anthropogenic pollutants. The data were downloaded from the Google Earth Engine's cloud-based geospatial data platform. This provided L3-level information for subsequent analysis. The TROPOMI data indicated a decrease in the atmospheric content of the air pollutants in the largest Russian cities during the lockdown compared to the pre-pandemic and post-pandemic periods. The reduced economic activity due to the COVID-19 pandemic had the greatest impact on NO_2 concentrations. The average reduction was −30.7%, while the maximum reduction was found within Moscow city limits that existed before 01.07.2012 (−41% with respect to the 2019 level). For sulfur dioxide, the average decrease was only 7%, with a further drop in 2021 (almost 20% relative to 2019). For formaldehyde and carbon monoxide, there were no reductions during the 2020 lockdown period (99.4% and 100.9%, respectively, with respect to 2019). The identified impacts of the COVID-19 lockdown on NO_2, SO_2, HCHO, and CO NO_2 concentrations in major Russian cities generally followed the patterns observed in other industrialized cities in China, India, Turkey, and European countries. The COVID-19 pandemic had a local impact on NO_2 concentration reductions in major Russian cities. The differences leveled off over time, and the baseline pollution level for each pollutant was restored.

Keywords: regional air pollution; air quality; city; remote sensing; TROPOMI; Google Earth Engine; Sentinel-5; COVID-19

check for updates

Citation: Morozova, A.; Sizov, O.; Elagin, P.; Lobzhanidze, N.; Fedash, A.; Mironova, M. Evaluation of the Impact of COVID-19 Restrictions on Air Pollution in Russia's Largest Cities. *Atmosphere* **2023**, *14*, 975. https://doi.org/10.3390/atmos14060975

Academic Editor: Sergey Gromov

Received: 27 April 2023
Revised: 23 May 2023
Accepted: 27 April 2023
Published: 2 June 2023

Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The first case of COVID-19, which is caused by the SARS-CoV-2 virus (severe acute respiratory syndrome coronavirus 2), was reported in Wuhan, China in December 2019 [1]. COVID-19 quickly spread across the world and was declared a pandemic by the World Health Organization (WHO) on 11 March 2020. As of February 10, 2023, there were 755,385,709 confirmed COVID-19 cases and 6,833,388 deaths worldwide (https://covid19.who.int (accessed on 10 February 2023) [2]. To limit the transmission of COVID-19, many countries imposed lockdown and isolation measures, resulting in reduced industrial

activity, transportation, and movement of people. Only major industries and services were allowed to operate, which led to severe economic consequences [3].

The decline in economic activity also affected the air quality in major cities and industrial clusters around the world [4–8]. Reductions in major air pollutants [2], such as nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and formaldehyde (HCHO) (List of pollutants subject to state regulation measures in the field of environmental protection [9]), were reported in many cities during the lockdown. In particular, significant (~70%) NO_2 reductions were observed in Spain, Italy [10] and India [11]; SO_2 reductions were reported in India (~62% [12]) and Singapore (~52% [13]) and CO reductions were reported in Brazil (>30% to 100% [14]) and India (~70% [12]). The lower concentrations of primary air pollutants were mostly caused by reductions in air pollutant emissions from motor vehicles and secondary industries [15,16]. We studied the variations in air quality by using measurements taken by stationary monitoring stations and satellite observation [5,17–21]. The effect of COVID-19 on air quality at the national level in Russia was not analyzed in detail [22–24]. This is the first study of the air conditions in Russia's largest cities during the COVID-19 pandemic.

Air pollution has dangerous consequences. It is a factor that can contribute to increased severity of COVID-19 and an increase in mortality associated with the disease [25]. In addition to health risks, air pollution contributes to climate change [26] and is harmful in uplands [27].

Recently, the capabilities of atmospheric remote sensing have significantly increased. In particular, a number of satellites were launched into orbit to measure the vertical distribution of such chemicals as ozone, nitrogen dioxide, methane, carbon monoxide, water vapor, aerosols, etc. (SCISAT-1, 2003, Canada; Aura, 2004, USA; GOSAT, 2009, Japan; GOSAT-2, 2018, Japan, etc.) [28–31]. The Tropospheric Monitoring Instrument (TROPOMI) [32,33] is the most advanced and affordable source of information about current atmospheric pollutant levels on a global scale [32,34].

The TROPOMI (Tropospheric Monitoring Instrument) spectrometer on the Sentinel-5P satellite (launched on 13 October 2017) is designed for daily global atmospheric monitoring under the EU Copernicus program [35]. The integration of the TROPOMI dataset with the Google Earth Engine's cloud platform has significantly expanded information analysis capabilities [34].

We studied TROPOMI data for the largest Russian cities (with over 250,000 citizens) to estimate the impacts of the first and largest nation-wide lockdown in the first half of 2020 on air pollution from NO_2, SO_2, HCHO, and CO.

2. Materials and Methods

We selected 78 Russian cities with populations exceeding 250,000 (as of 1 January 2020); 60.63% of the Russian population lives in these cities (Table 1). The official city limits were obtained as vector images by digitizing the cities' master plans (available from the Federal Government Terrain Planning System, 2020 [36]). The official city limits were relatively stable, so we could compare year-to-year pollution levels in each city and analyze the root causes of negative or positive changes in detail.

Table 1. Largest Russian cities.

No.	Name	Region	pop	area_sqkm
1.	Moscow *	Moscow	12,678,079	2549.7
2.	Saint Petersburg	St. Petersburg	5,398,064	493.6
3.	Novosibirsk	Novosibirsk Region	1,625,631	555.5

Table 1. *Cont.*

No.	Name	Region	pop	area_sqkm
4.	Yekaterinburg	Sverdlovsk Region	1,493,749	469.2
5.	Kazan	Republic of Tatarstan	1,257,391	614.1
6.	Nizhny Novgorod	Nizhny Novgorod Region	1,252,236	500.8
7.	Chelyabinsk	Chelyabinsk Region	1,196,680	597.6
8.	Samara	Samara Region	1,156,659	541.9
9.	Omsk	Omsk Region	1,154,507	340.5
10.	Rostov-on-Don	Rostov Region	1,137,904	852.6
11.	Ufa	Republic of Bashkortostan	1,128,787	378.4
12.	Krasnoyarsk	Krasnoyarsk Territory	1,093,771	810.8
13.	Voronezh	Voronezh Region	1,058,261	599.4
14.	Perm	Perm Territory	1,055,397	845.3
15.	Volgograd	Volgograd Region	1,008,998	339.6
16.	Krasnodar	Krasnodar Territory	932,629	385.1
17.	Saratov	Saratov Region	838,042	473.2
18.	Tyumen	Tyumen Region	807,271	270.7
19.	Togliatti	Samara Region	699,429	318.5
20.	Izhevsk	Udmurt Republic	648,146	331.1
21.	Barnaul	Altai Territory	632,391	277.3
22.	Ulyanovsk	Ulyanovsk Region	627,705	544.8
23.	Irkutsk	Irkutsk Region	623,562	383.7
24.	Khabarovsk	Khabarovsk Territory	616,372	213.2
25.	Yaroslavl	Yaroslavl Region	608,353	325.1
26.	Vladivostok	Primorsky Territory	606,561	501.7
27.	Makhachkala	Republic of Dagestan	603,518	258.3
28.	Tomsk	Tomsk Region	576,624	340.9
29.	Orenburg	Orenburg Region	572,188	318.9
30.	Kemerovo	Kemerovo Region (Kuzbass)	556,382	495.6
31.	Novokuznetsk	Kemerovo Region (Kuzbass)	549,403	223.9
32.	Ryazan	Ryazan Region	539,290	212.8
33.	Naberezhnye Chelny	Republic of Tatarstan	533,839	166.7
34.	Astrakhan	Astrakhan Region	529,793	299.1
35.	Penza	Penza Region	520,300	360.8
36.	Kirov	Kirov Region	518,348	177.3
37.	Lipetsk	Lipetsk Region	508,573	164
38.	Balashikha	Moscow Region	507,366	111.9
39.	Cheboksary	Chuvash Republic	497,618	224.6
40.	Kaliningrad	Kaliningrad Region	489,359	191.7
41.	Tula	Tula Region	475,161	378.7
42.	Kursk	Kursk Region	452,976	175.8
43.	Stavropol	Stavropol Territory	450,680	81.4

Table 1. *Cont.*

No.	Name	Region	pop	area_sqkm
44.	Sevastopol	Sevastopol City	449,138	395.3
45.	Sochi	Krasnodar Territory	443,562	143.1
46.	Ulan-Ude	Republic of Buryatia	439,128	105.6
47.	Tver	Tver Region	425,072	153.1
48.	Magnitogorsk	Chelyabinsk Region	413,253	222.5
49.	Ivanovo	Ivanovo Region	404,598	161.7
50.	Bryansk	Bryansk Region	402,675	304
51.	Belgorod	Belgorod Region	394,142	141.5
52.	Surgut	Khanty-Mansi Autonomous Okrug (Ugra)	380,632	254.1
53.	Vladimir	Vladimir Region	356,937	215
54.	Chita	Zabaikalsky Territory	351,784	375
55.	Nizhny Tagil	Sverdlovsk Region	349,008	165.4
56.	Arkhangelsk	Arkhangelsk Region	346,979	170.8
57.	Simferopol	Republic of Crimea	342,054	216.6
58.	Kaluga	Kaluga Region	332,039	392.5
59.	Smolensk	Smolensk Region	325,495	122
60.	Volzhsky	Volgograd Region	323,906	115.1
61.	Yakutsk	Republic of Sakha (Yakutia)	322,987	170.6
62.	Saransk	Republic of Mordovia	320,612	84.7
63.	Cherepovets	Vologda Region	314,834	290.7
64.	Kurgan	Kurgan Region	312,364	173.9
65.	Vologda	Vologda Region	310,302	166.2
66.	Orel	Oryol Region	308,838	40.4
67.	Podolsk	Moscow Region	308,130	98.5
68.	Grozny	Chechen Republic	305,911	298.8
69.	Vladikavkaz	Republic of North Ossetia (Alania)	303,597	132.2
70.	Tambov	Tambov Region	292,140	114.3
71.	Murmansk	Murmansk Region	287,847	135.2
72.	Petrozavodsk	Republic of Karelia	281,023	271.8
73.	Nizhnevartovsk	Khanty-Mansi Autonomous Okrug (Ugra)	277,668	75.2
74.	Kostroma	Kostroma Region	276,929	99.3
75.	Sterlitamak	Republic of Bashkortostan	276,394	61.2
76.	Novorossiysk	Krasnodar Territory	274,956	1447.1
77.	Yoshkar-Ola	Republic of Mari El	274,715	103.7
78.	Khimki	Moscow Region	259,550	96.9

* Hereinafter, Moscow is divided into two entities: Moscow and New Moscow. Moscow refers to the territory within the city limits that existed before 1 July 2012. New Moscow also includes the Novomoskovsk, Troitsk, and Zapadny districts.

To stop the spread of COVID-19 in Russia, 30 March through 11 May 2020 were declared days off at the national level. The nationwide decline in economic activity was confirmed by a higher shelter-in-place index, as estimated from the usage rate of Yandex applications/services (Yandex Shelter-In-Place Index [37,38]). The index is an integrated

indicator that is calculated with data on the use of various Yandex applications and services based on levels of urban activity. It ranges from 0 (no self-isolation) to 5 (complete self-isolation) [39]. Later, complete lockdowns (days off) were introduced in some Russian regions from 4–7 May 2021, from 12–21 June 2021, and from 30 October–7 November 2021. Local governments, social services, and schools were closed. Catering and retail businesses operated as usual. The first lockdown in early 2020 was the only opportunity to assess the impact of the COVID-19 pandemic on air pollution nationwide, since all of the subsequent restrictions were either local or not mandatory. Therefore, we studied the period of the first lockdown, from 30 March 30–11 May 2020 [40–42].

The TROPOMI spectrometer conducts surveys in the ultraviolet (UV), visible (VIS), near-infrared (NIR), and mid-infrared (SWIR) electromagnetic ranges. The instrument determines the total content of such chemicals as O_3 (mol/m^2), NO_2 (mol/m^2), SO_2 (mol/m^2), CO (mol/m^2), CH_4 (ppbV), and HCHO (mol/m^2) in the vertical column of the troposphere. The aerosol index (AI) is also estimated. The swath width is 2600 km. Spatial resolution varies depending on the substance surveyed: 7×3.5 km^2 for SO_2, NO_2, HCHO, and aerosols; and 7×7 km^2 for CO and CH_4, and 28×21 km^2 for O_3 [35].

We used the Google Earth Engine (GEE) API [34] to access the TROPOMI dataset. The TROPOMI dataset is presented on the GEE cloud platform as Sentinel collections for each chemical substance. Each collection is an L3-processing-level data cube. For easier analysis, the L2 datasets were divided into a regular grid for each orbit without aggregating by component. The default quality thresholds for the resulting datasets were 80% for the aerosol index, 75% for NO_2, and 50% for all other substances. Each pixel in the data cube could be processed with many statistical and spatial analysis tools without any preprocessing.

To analyze the TROPOMI datasets [43] available on the GEE, we used the embedded Code Editor interface to develop scripts and user-defined libraries that achieved the following:

- Downloading data and filtering them by date and other conditions;
- Property aggregation in collection and calculation of the average, minimum, and maximum values for the specified property;
- Statistics by area (within the city limits);
- Merging of multi-temporal images;
- Addition, subtraction, multiplication, and division;
- Auxiliary operations;
- Reporting.

The TROPOMI datasets were filtered, and we replaced the negative values with 0. Negative SO_2 concentrations could be registered in a clear sky or when the pollutant level was below the threshold (Google Earth Engine 2021). Noise in the data could also generate negative values. The Google Earth Engine Data Catalog does not recommend filtering out negative values except for outliers, i.e., vertical columns with concentrations below -0.001 mol/m^2.

There is no common scientific approach to assessing the COVID-19 pandemic's impact on air pollution. For example, some studies compared air pollutant levels registered during a lockdown with those for the same year before and/or after the lockdown [14,44,45]. Other studies considered either the same period for the previous years (2019/2018/2017) [46–48] or a combination of both of the periods [49].

In this study, the pollution level in 2020 was compared with the pollution levels in 2019 and 2021. The period of March 29 to June 13 in each year was considered, since it was the period of the national lockdown in 2020 (refer to Figure 1). The daily measurements were aggregated every 7 days, since this is the weekly business activity cycle in these cities. This was also confirmed by the Yandex Activity Index.

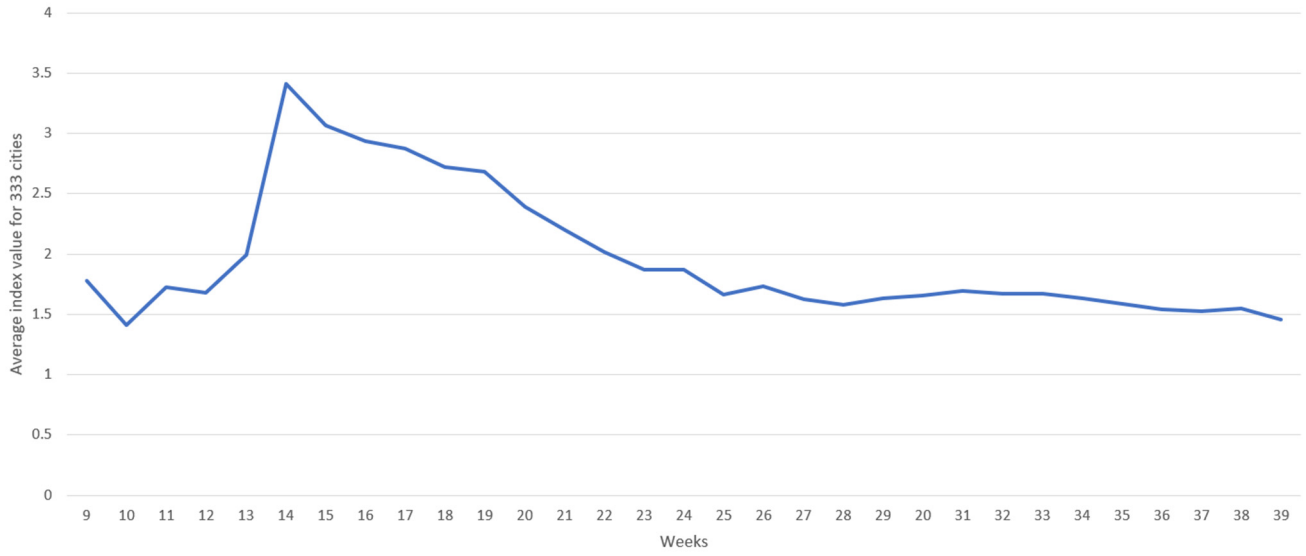


Figure 1. Shelter-in-place index vs. date (average for the cities studied).

This study used the daily average concentrations of NO_2, SO_2, CO, and HCHO. The largest cities produced most of the air pollution. The emission sources were usually located within a city or near it [50–52]. It was also shown that the urban infrastructure itself greatly impacted the pollutant concentration [53–55] (heat island effect).

The final statistical data were obtained in MS Excel 2019, and thematic maps were generated in QGIS v.3.20.

3. Results

The results of this study are presented in two ways:

- The average column-integrated results for each pollutant for the entire sample dataset (78 cities) for every 7 days;
- The average column-integrated results for each pollutant and each city for the entire period (March 29 to June 13 of each year).

3.1. Weekly Concentrations Trends

For nitrogen dioxide, the 2020 pollution level was 69.3% of the 2019 level and 77.1% of the 2021 level. The 2021 pollution level was 93.9% of the 2019 level. There was a clear trend of decreasing pollution in 2020 (compared to 2019) immediately after the lockdown began. The concentration levels were restored by the end of the period (refer to Figure 2).

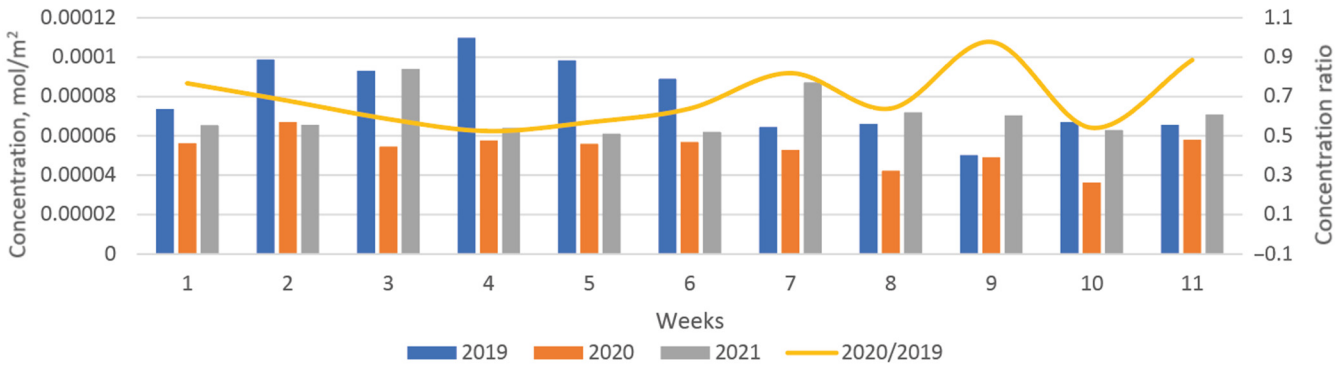


Figure 2. Weekly NO_2 concentrations trends (all of the cities).

For sulfur dioxide, the 2020 pollution level was 94.0% of the 2019 level and 120.3% of the 2021 level. The 2021 pollution level was 80.4% of the 2019 level. The trends at

the beginning of the lockdown showed a significant increase in pollution in 2020 relative to 2019, followed by a sharp decrease from week 3 to week 6. After that, starting from week 7, the pollution leveled off (with a slight predominance of decreasing). Note that the 2021 pollution levels were significantly lower than those in 2020 and 2019. This may be attributed to the inconsistent recovery of industrial production after the pandemic (refer to Figure 3).

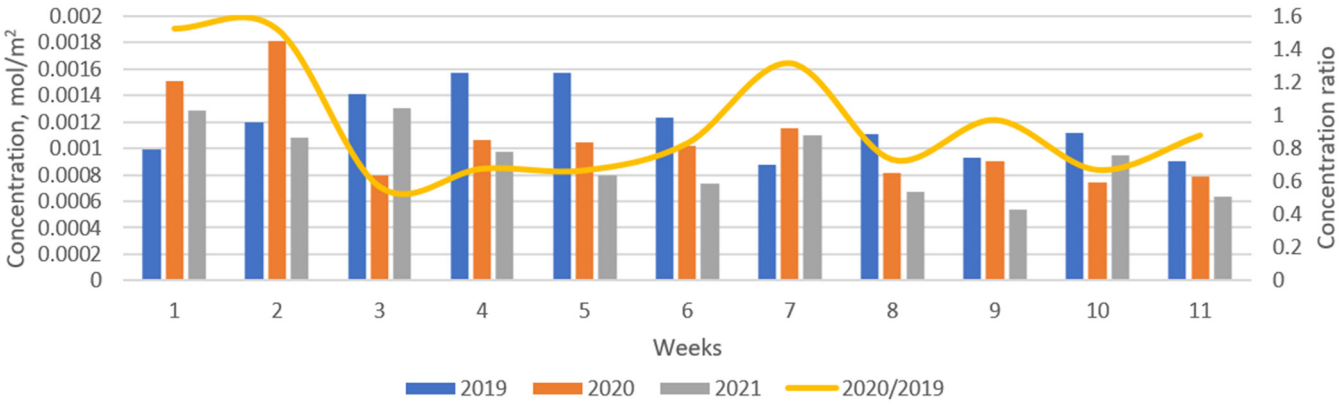


Figure 3. Weekly SO_2 concentrations trends (all of the cities).

For formaldehyde, the 2020 pollution level was 99.5% of the 2019 level and 114.7% of the 2021 level. The 2021 pollution level was 90.0% of the 2019 level. The trends at the beginning of the lockdown showed an increase in pollution in 2020 relative to 2019. After that, the figures generally leveled off. The pollution in 2021 was also below the values in 2020 and 2019 (refer to Figure 4).

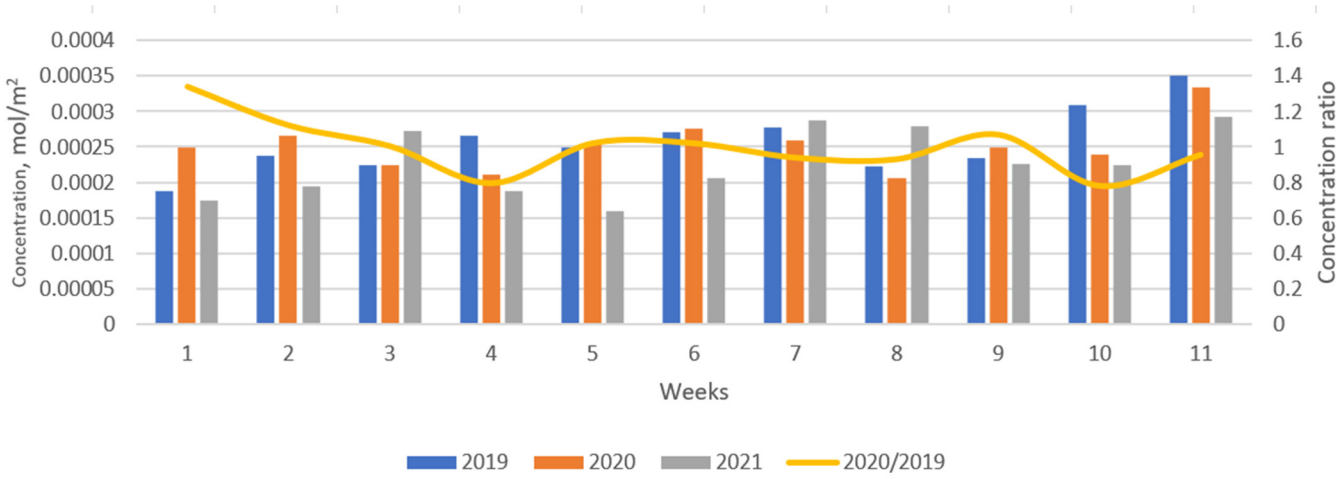


Figure 4. Weekly HCHO concentrations trends (all of the cities).

The column-integrated results for carbon monoxide were virtually identical in 2019–2021. The 2020 pollution level was 100.7% of the 2019 level and 100.4% of the 2021 level. The 2021 pollution level was 100.3% of the 2019 level. There were no clear trends (refer to Figure 5).

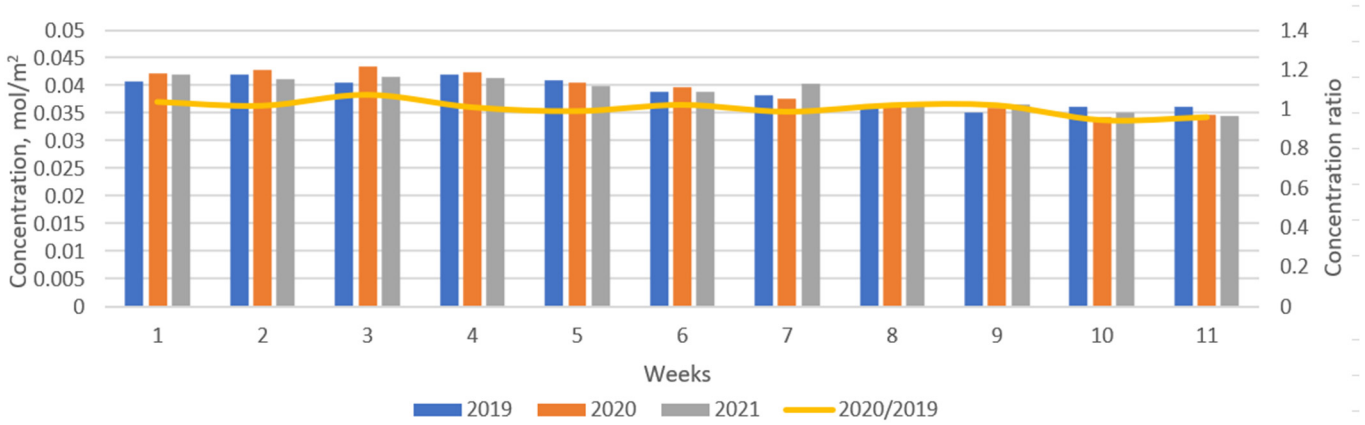


Figure 5. Weekly CO concentrations trends (all of the cities).

3.2. Concentrations by City

NO_2: The 2020/2019 pollution ratio, which is expressed as a bar chart, shows two groups of cities. In one group, the pollution decreased to 60%, and in the other, it decreased to 80% (16 and 24 cities, respectively), with an overall decrease in 2020 to 74.1% of the 2019 level. Five cities had pollution levels higher than those in 2019 (Tomsk, Novokuznetsk, Stavropol, Kemerovo, and Volzhsky). The largest decreases in 2020 occurred in Moscow (old city limits), Podolsk, and New Moscow (up to 41%, 34%, and 29% of the 2019 values, respectively) (refer to Figure 6). The pollution levels in the cities were mostly restored by 2021 (the 2021 to 2019 ratio was 97.6%). The bar chart shows three distinct groups: in 8 cities, the pollution was reduced to 60%; in 19 cities, it dropped to 80%; in 14 cities, it increased to 110% (refer to Figure 7a,b).

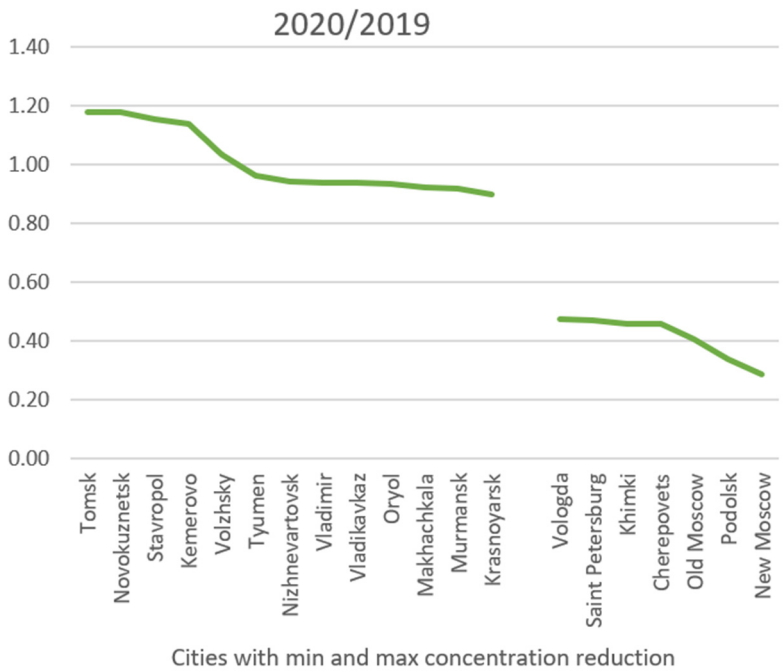
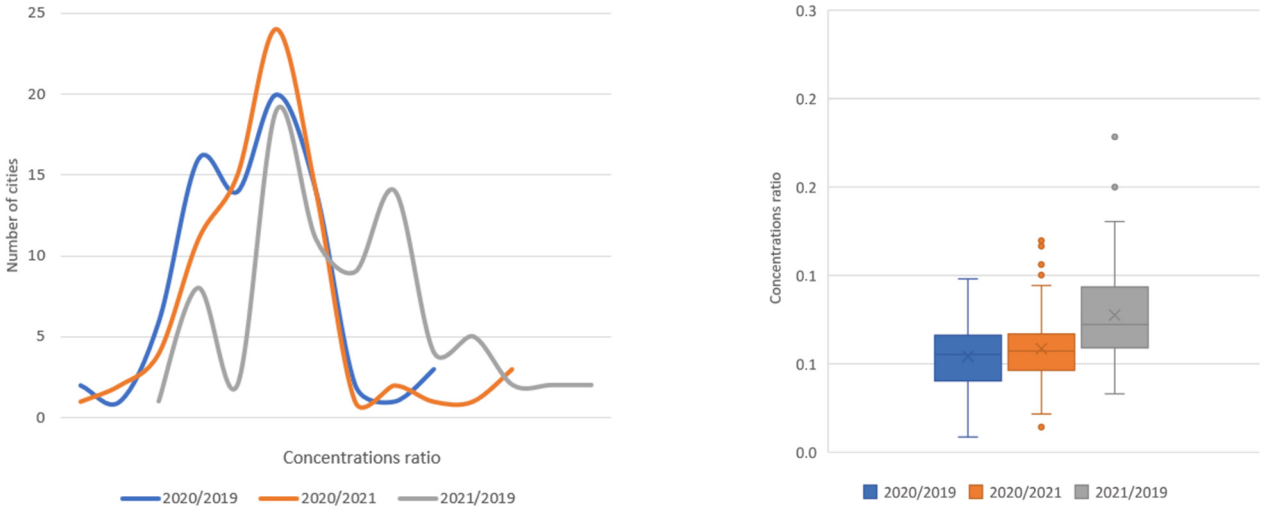


Figure 6. Spatial distribution of the 2020/2019 NO_2 pollution levels.



(**a**) (**b**)

Figure 7. (**a**) Bar chart and box plot of the 2020/2019, (**b**) 2020/2021, and 2021/2019 NO_2 concentrations ratio distributions.

SO_2: The 2020/2019 pollution ratio, which is expressed as a bar chart, shows that there was a dominant group with a decrease of up to 90% (17 cities). The average decrease for all of the cities was only about 7% (16 and 24 cities, respectively). Almost half of the cities (32) featured no changes or increases in pollution during the 2020 lockdown compared to 2019. The leaders in terms of pollution growth were Sevastopol, Simferopol, and Novorossiysk (up to 160%, 157%, and 140% of the 2019 level, respectively). The largest reductions were found in Orel, Tula, and Sterlitamak (up to 48%, 52%, and 53% of the 2019 level, respectively) (refer to Figure 8). In general, the pollution levels in the cities did not return to the pre-pandemic levels in 2021 (the 2021 to 2019 ratio was only 77.2%); only 19 cities (24%) had no changes or an increase in their SO_2 concentrations (refer to Figure 9a,b).

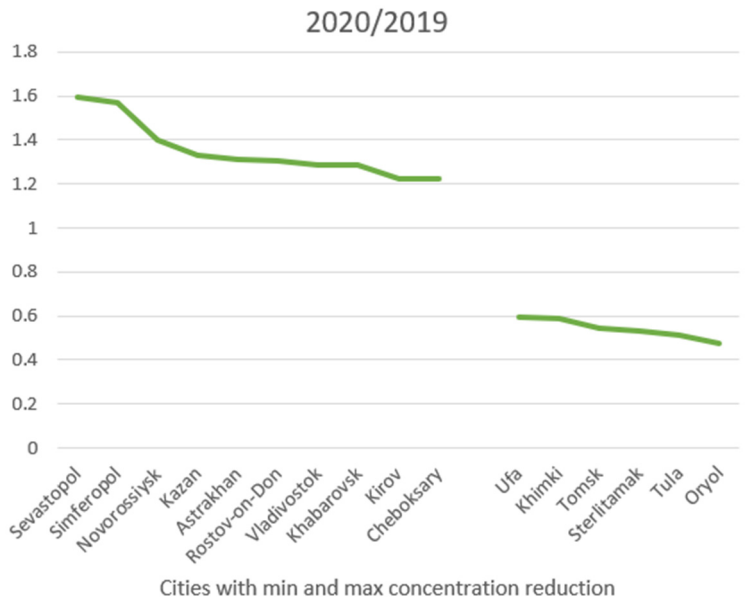
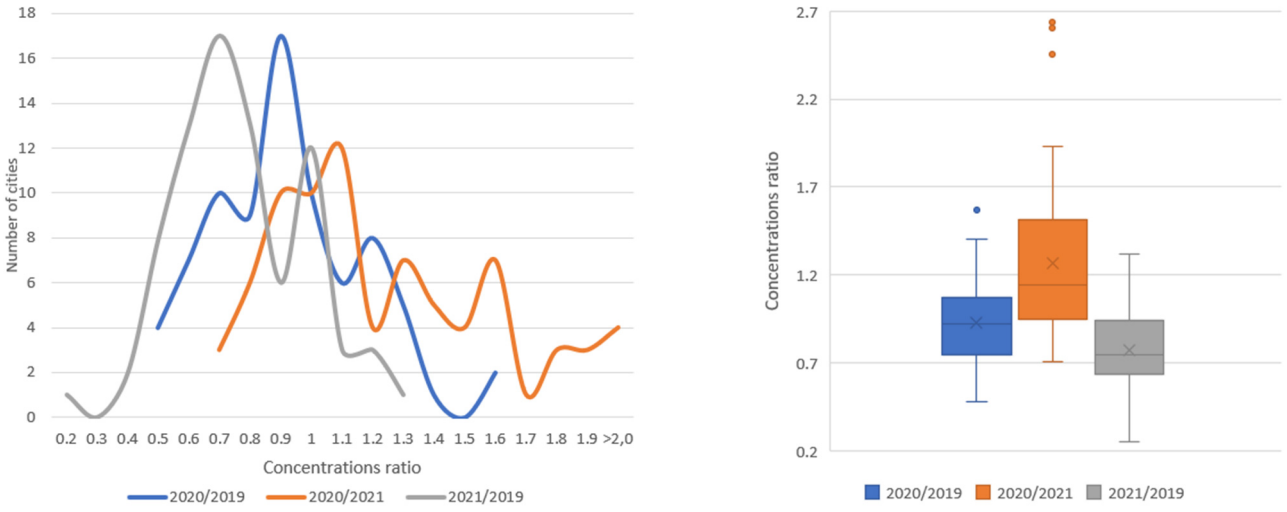


Figure 8. Spatial distribution of the 2020/2019 SO_2 pollution levels.



(**a**) (**b**)

Figure 9. (**a**) Bar chart and box plot of the 2020/2019; (**b**) 2020/2021 and 2021/2019 SO_2 concentrations ratio distributions.

HCHO: The 2020/2019 pollution ratio, which is expressed as a bar chart, shows that there were two groups of cities: those with a decrease to 80% and those with no changes (15 and 20 cities, respectively). There were no overall reductions in pollution in 2020 (99.4% of the 2019 level). The leaders in pollution growth were Nizhnevartovsk, Stavropol, and Kemerovo (up to 179%, 142%, and 132% of the 2019 level, respectively). The leaders in pollution decline were Orel, Tver, and Podolsk (up to 61%, 68%, and 70% of the 2019 level, respectively) (refer to Figure 10). In 2021, there was a slight decrease (to 91.3% of the 2019 level). A total of 34 cities (43%) showed no changes or an increase in HCHO NO_2 concentrations (refer to Figure 11a,b).

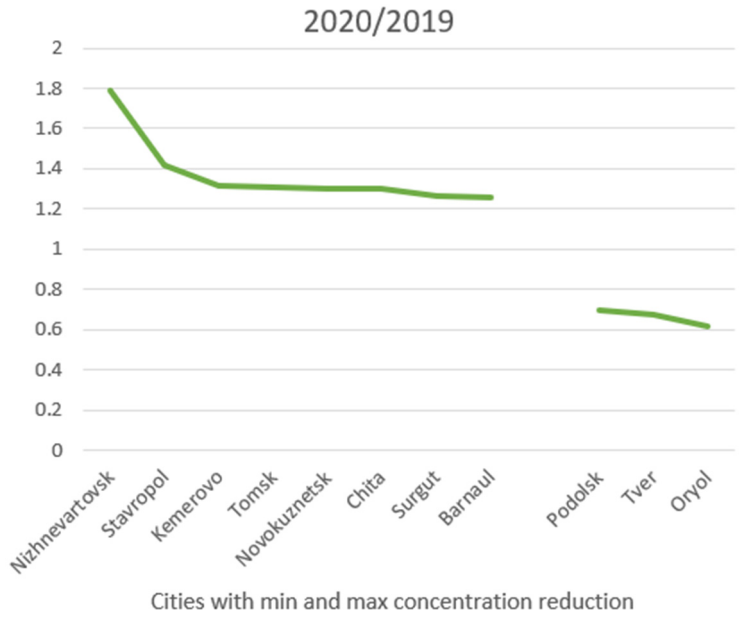
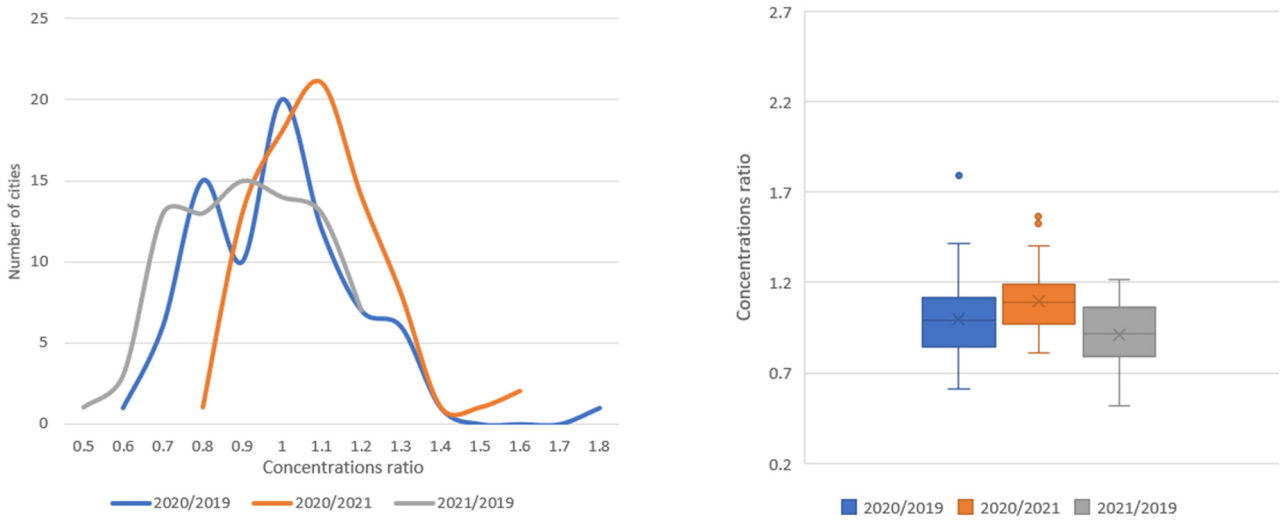


Figure 10. Spatial distribution of the 2020/2019 HCHO pollution levels.



(**a**) (**b**)

Figure 11. (**a**) Bar chart and box plot of 2020/2019; (**b**) 2020/2021 and 2021/2019 HCHO concentrations ratio distributions.

CO: The 2020/2019, 2020/2021, and 2021/2019 pollution ratios were, in general, evenly distributed (100.9%, 100.6%, and 100.3%, respectively) (refer to Figure 12). We identified the cities with relatively high pollution growth in 2020—Chita, Surgut, and Novorossiysk (112%, 107%, and 107% of the 2019 level, respectively)—as well as the cities with the largest declines: Moscow (within its old city limits), Cherepovets, and Lipetsk (94% of the 2019 level for all cities) (refer to Figure 13a,b).

In general, the 2020 lockdown affected the concentrations of NO_2 and SO_2. The formaldehyde and carbon monoxide levels were not affected.

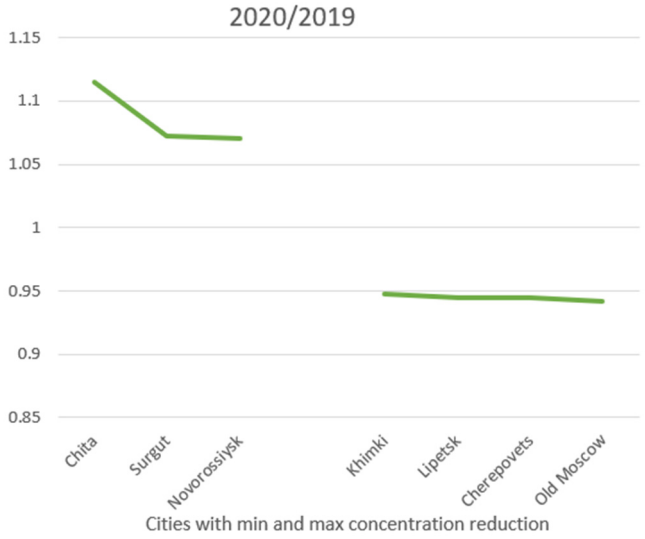
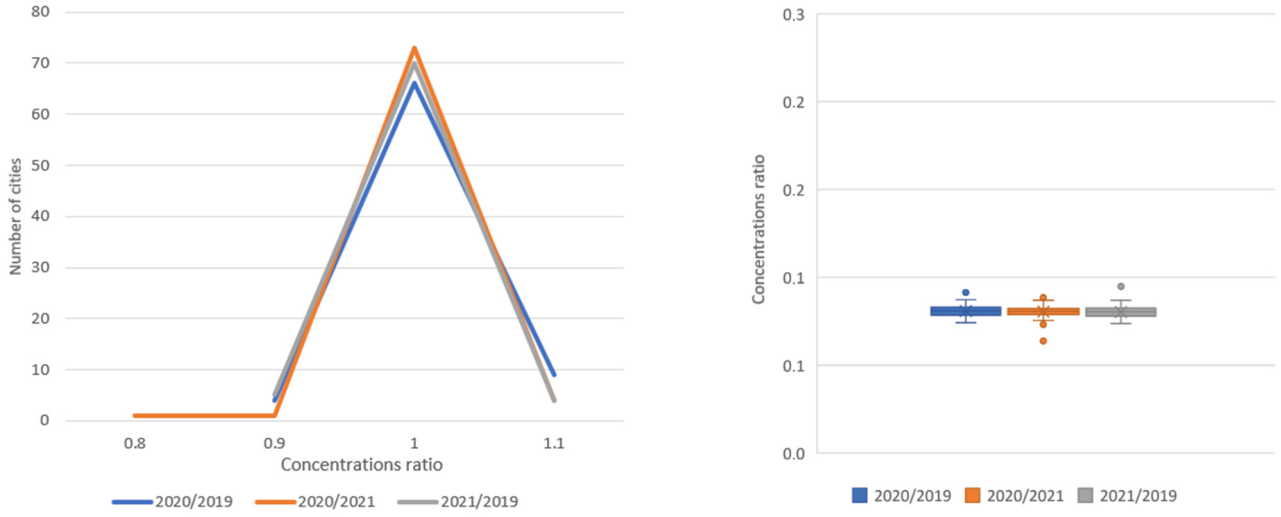


Figure 12. Spatial distribution of the 2020/2019 CO pollution levels.



(**a**) (**b**)

Figure 13. (**a**) Bar chart and box plot of 2020/2019; (**b**) 2020/2021 and 2021/2019 CO concentrations ratio distributions.

4. Discussion

NO_2: Many studies have shown that the reduction in economic activity during the COVID-19 lockdown mostly reduced NO_2 emissions (caused by fossil fuel combustion by vehicles and power plants) [56–59]. Some studies reported that the largest NO_2 emission reductions were in cities that introduced a shelter-in-place policy [60]. The dramatic reduction in the use of private cars and public transport vehicles during the lockdown led to an equally dramatic reduction in NO_2 emissions [61].

In this respect, the results for the largest Russian cities were in good agreement with those of other cities of the world. Note that the 30.7% average NO_2 reduction in 2020 relative to 2019 was comparable to the figures for the southeast of the United Kingdom (33% reduction) [62] and significantly below the level reported in China (54% reduction for 336 cities) [63]. According to Sicard et al. (2020) [10], the lockdowns in China (Wuhan) and in four European cities (Nice, Rome, Valencia, and Torino) dramatically reduced concentrations of air pollutants, especially NO_2, by about 56% in all the cities. Moscow (within the old city limits that existed before 2012) exceeded all major European cities in NO_2 reductions (59%). The maximum reduction in Europe was in Paris (46%).

We should also note the varying NO_2 concentration reduction rates for the Russian cities under consideration. This can be explained both by the inconsistent enforcement of lockdowns and the specific features of the local economies. For example, if we compare Moscow with Novokuznetsk, the activity of the populations during the 2020 lockdown differed by more than 60% (refer to Figure 14). At the same time, the concentrations in Novokuznetsk did not depend on population activity. The concentrations mostly followed the production cycles of the large local smelters located within the city limits (refer to Figure 14). The decline in industrial output in Novokuznetsk may be the reason for the further decrease in concentrations in 2021, while in Moscow, the concentrations levels mostly recovered (refer to Figure 15).

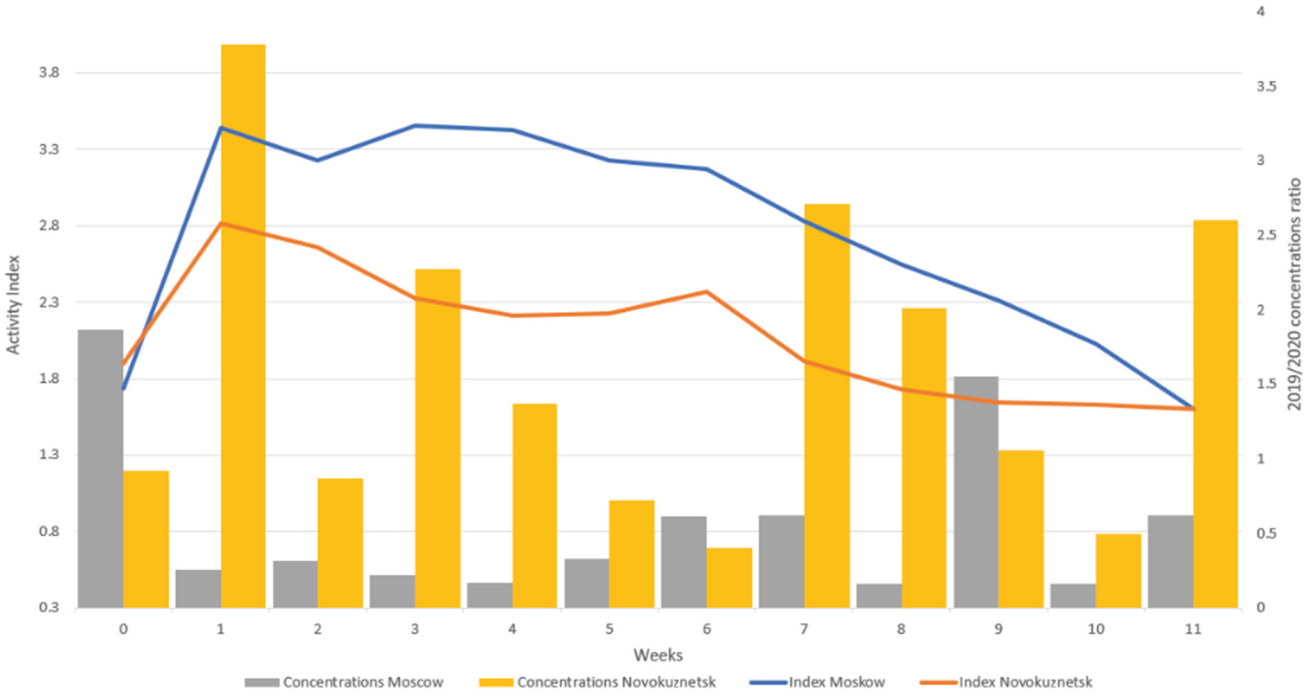


Figure 14. Activity index vs. NO_2 concentrations in 2020 for Moscow and Novokuznetsk.

With an overall decrease in 2020 (up to 74.1% relative to 2019), five cities featured pollution levels higher than those in 2019 (Tomsk, Novokuznetsk, Stavropol, Kemerovo, and Volzhsky). These are highly industrialized cities. The high pollution in 2020 relative to 2019 could be attributed to the fact that the local industries did not stop in these cities and to poor lockdown enforcement.

SO_2: Air pollution from SO_2 is independent of populations' activities (transport) and is strongly associated with the burning of coal for energy generation and the production of non-ferrous metals (nickel, copper, etc.) [64,65]. Therefore, the available studies for cities and urban agglomerations showed multidirectional effects of the COVID-19 pandemic on SO_2 emissions. For example, there was a 15.6% decrease in Egypt, while Turkey and France showed an increase [66–68]. Considering the widespread use of coal-fired generation in Russian cities, the concentrations were reduced by only 7%. Following the announcement of the lockdown, production in Siberia began to increase due to concerns about restrictive measures. From weeks 3 to 6, the restrictions began to be implemented (the level of pollution decreased). After the seventh week, the governors relaxed restrictions on industrial enterprises (the level remained stable) [39].

More noteworthy is the further drop in concentrations in 2021 (almost 20% relative to 2019). It can be attributed to the decline in industrial production and electricity generation. This is clear when comparing Rostov-on-Don with Nizhny Tagil (refer to Figure 15). Rostov-on-Don used coal at a rate that was not correlated with population activity. This is why electricity consumption and SO_2 pollution in 2020 increased compared to 2019 (emissions from stationary sources, as reported by the Federal Service for Supervision of Natural Resources) [69]. The concentrations in Nizhny Tagil decreased in 2020 and 2021. The reason was most probably the decline in smelter production (as indicated by the OKVED 2 Production Index) [70].

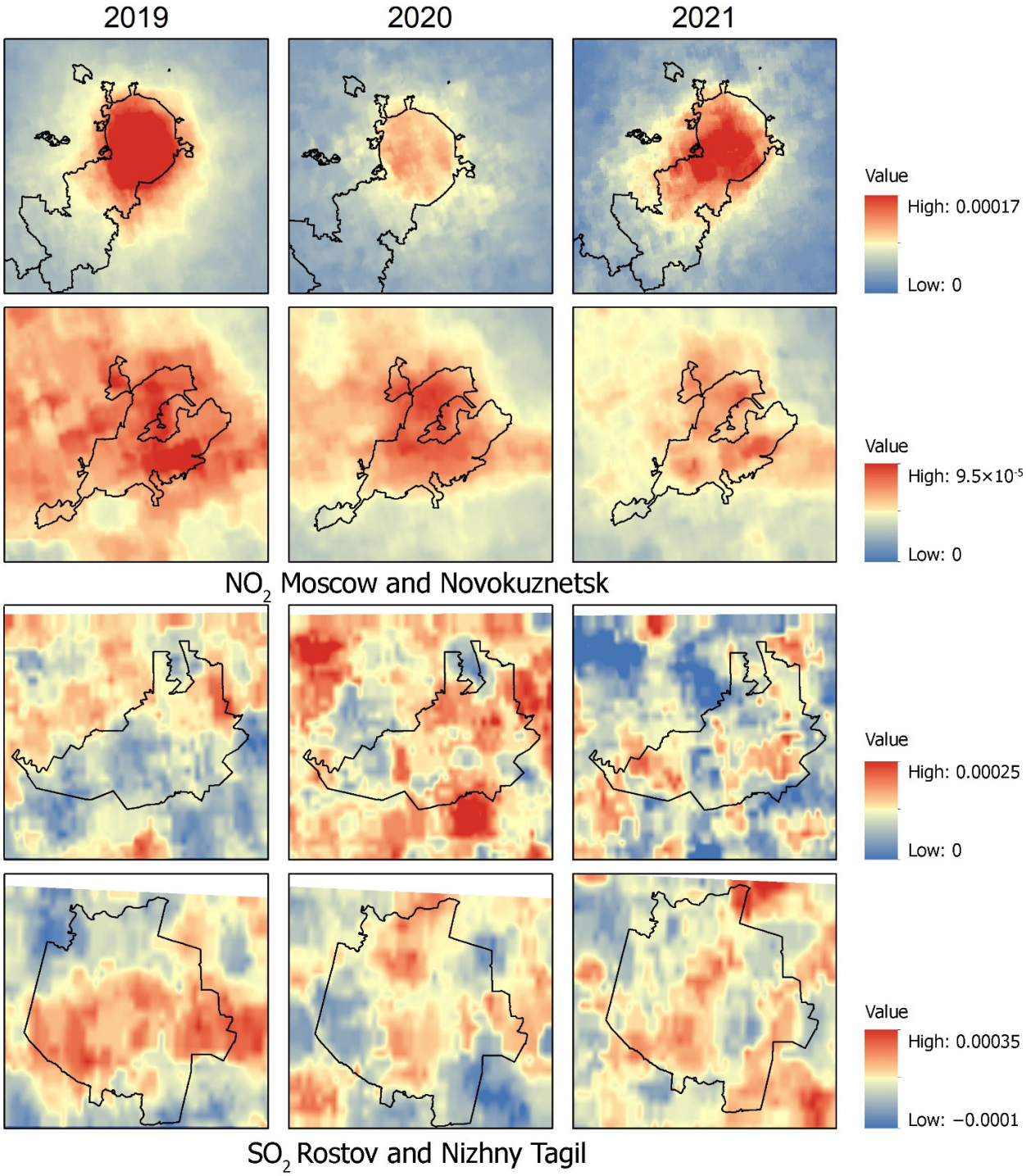


Figure 15. Map of NO_2 and SO_2 content for 3 years in the selected cities.

It is also noted that SO_2 pollution in 2021 was significantly lower than in 2020 and 2019. This can be explained by the inconsistent recovery of production after the pandemic. As the OKVED2 Production Index indicates, the industrial output in 2021 remained about the same as in 2019. That said, when comparing April 2019 with April 2021 across industries, we saw that not all industries fully recovered, as indicated by the OKVED2 Production Index (mining (96 vs. 98), manufacturing (100 vs. 96), coke and petroleum products (93 vs. 95), and metals (102 vs. 96)).

CO and HCHO: As for formaldehyde and carbon monoxide, several studies (with few exceptions) were observed. This was in full agreement with this study: HCHO

concentration levels and trends in Russia showed no signs of dependence on COVID-19 restrictions. This applied to both the average values for the entire dataset and the standard deviations for the largest cities. While the formaldehyde concentrations showed small seasonal fluctuations, the CO content was virtually stable over the entire period for all 78 cities.

It can be noted that the impact of the COVID-19 lockdown on NO_2, SO_2, HCHO, and CO concentrations in major Russian cities generally coincided with the situations in other industrialized cities in China, India, Turkey, and European countries (Table 2).

Table 2. Decreases in NO_2 and CO pollution in European cities during the COVID-19 lockdown.

City	Country	Reduction Date	Link
Paris	France	NO_2 (−46%), CO (−2.4%) NO_2 (−29%) NO_2 (−40%)	Sannigrahi et al., 2021 [71] Barré et al., 2021 [72] Bar et al., 2021 [73]
London	UK	NO_2 (−33%), NO_2 (−34%), CO (−1%) NO_2 (−30%)	Wyche et al., 2021 [62] Sannigrahi et al., 2021 [71] Barré et al., 2021 [72]
Milan	Italy	NO_2 (−37%), CO (−3.2%) NO_2 (−31%)	Sannigrahi et al., 2021 [71] Bar et al., 2021 [73]
Torino	Italy	NO_2 (−54%) NO_2 (−37%)	Barré et al., 2021 [72] Sannigrahi et al., 2021 [71]
Frankfurt	Germany	NO_2 (−24%) NO_2 (−36%), CO (−0.7%)	Barré et al., 2021 [72] Sannigrahi et al., 2021 [71]
Madrid	Spain	NO_2 (−60%), NO_2 (−34%), CO (−1.3%) NO_2 (−21%)	Barré et al., 2021 [72] Sannigrahi et al., 2021 [71] Bar et al., 2021 [73]
Rotterdam	Netherlands	NO_2 (−27%), CO (−0.01%) NO_2 (−13%),	Sannigrahi et al., 2021 [71] Barré et al., 2021 [72]
Antwerp	Belgium	NO_2 (−24%), CO (−1.4%) NO_2 (−23%),	Sannigrahi et al., 2021 [71] Barré et al., 2021 [72]
Barcelona	Spain	NO_2 (−29.4%), CO (−2.86%) NO_2 (−59%),	Sannigrahi et al., 2021 [71] Barré et al., 2021 [72]
Brussels	Belgium	NO_2 (−29%), NO_2 (−27.9%), CO (−0.10%)	Barré et al., 2021 [72] Sannigrahi et al., 2021 [71]
Stockholm	Sweden	NO_2 (−17%) NO_2 (−19.4%)	Barré et al., 2021 [72] Bar et al., 2021 [73]
Warsaw	Poland	NO_2 (−30%) NO_2 (−6%)	Barré et al., 2021 [72] Bar et al., 2021 [73]
Amsterdam	Netherlands	NO_2 (−17%)	Barré et al., 2021 [72]
Berlin	Germany	NO_2 (−38%)	Barré et al., 2021 [72]
Helsinki	Finland	NO_2 (−28%)	Barré et al., 2021 [72]
Oslo	Norway	NO_2 (−51%)	Barré et al., 2021 [72]
Rome	Italy	NO_2 (−40%)	Barré et al., 2021 [72]

The locations of the cities in question (2019/2020 concentration ratios) showed (refer to Figure 16) that the decrease in pollution in central Russia was more pronounced. This can be attributed to the more stringent enforcement of lockdowns.

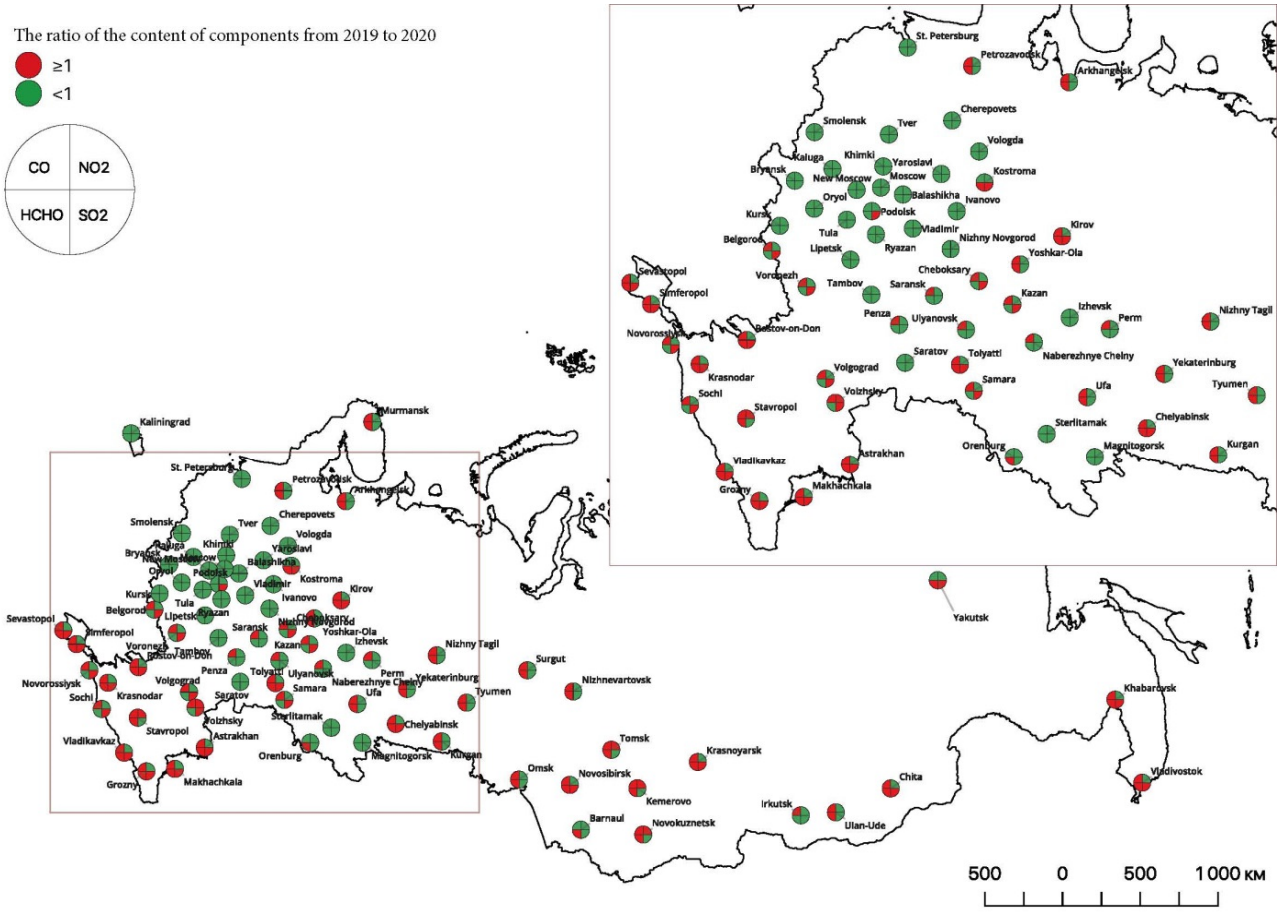


Figure 16. 2019/2020 concentration ratios.

The most significant impact on NO_2 concentration was the restriction of economic activity due to the COVID-19 pandemic. This was due to the fact that the coronavirus pandemic caused an emergency transition of all spheres of life to a digital format (Unesco) [74,75], so people began to use public and private transport less. For example, the absolute majority of companies in Russia (94%) organized off-site work for their employees. Up to February 2022, 89% of employers had employees working remotely [76,77]. There was no 100% recovery of the pollution levels prior to COVID-19 in 2021.

5. Conclusions

We could draw the following conclusions:

1. With the TROPOMI (Sentinel-5P satellite) datasets integrated into the Google Earth Engine cloud platform, it was possible to monitor air pollution of urban areas by such substances as carbon monoxide (CO), formaldehyde (HCHO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2). The TROPOMI data indicated a decrease in the atmospheric content of these air pollutants in the largest Russian cities during the lockdown compared to the levels in the pre-pandemic and post-pandemic periods. This was the first time that such a study was conducted on the scale of Russia.
2. The reduced economic activity due to COVID-19 had the greatest impact on reducing NO_2 concentrations. The average concentration reduction in 2020 relative to 2019 was 30.7%. The maximum reductions in 2020 were found in Moscow (within the former city limits) (41% of the 2019 level), Podolsk, and New Moscow (34% and 29% of the 2019 levels, respectively). Five cities had pollution levels higher than in 2019 (Tomsk, Novokuznetsk, Stavropol, Kemerovo, and Volzhsky).

3. For sulfur dioxide, the decrease was only 7%. More noteworthy was the further drop in concentrations in 2021 (almost 20% relative to 2019). This can be attributed to the decline in industrial production and electricity generation. The largest reductions occurred in Orel, Tula, and Sterlitamak (48%, 52%, and 53% of 2019 levels, respectively). The leaders in pollution growth were Sevastopol, Simferopol, and Novorossiysk (up to 160%, 157%, and 140% of 2019 levels, respectively).
4. For formaldehyde, there were no reductions for any of the cities in 2020 (99.4% relative to 2019). The leaders in pollution growth were Nizhnevartovsk, Stavropol, and Kemerovo (up to 179%, 142%, and 132% of 2019 levels, respectively). The leaders in pollution decline were Orel, Tver, and Podolsk (up to 61%, 68%, and 70% of 2019 levels, respectively).
5. The distribution of CO concentrations ratios was fairly uniform (100.9%). We identified the following cities with relatively high pollution growth in 2020: Chita, Surgut, and Novorossiysk (112%, 107%, and 107% of 2019 levels, respectively); the cities with the largest declines were Moscow (within its old city limits), Cherepovets, and Lipetsk (94% of 2019 levels for all cities).
6. The effects of the COVID-19 lockdown on NO_2, SO_2, HCHO, and CO e concentrations in major Russian cities generally coincided with those in other industrialized cities of China, India, Turkey, and European countries. The maximum reductions were for NO_2. The effect on SO_2 concentrations was multidirectional and was more attributed to coal generation than to population activities. We found no effects of COVID-19 restrictions on carbon monoxide and formaldehyde concentrations.
7. The impact of the COVID-19 pandemic on the concentration reductions in large Russian cities was local (more reductions in the central part of the country), while, over time, the differences leveled off, and the baseline pollution levels for all of the components under consideration were restored.

This study was carried out as part of the implementation of a scientific research project of the National Research University "Gubkin Russian State University of Oil and Gas" with the support of the Strelka KB consulting company.

Author Contributions: Conceptualization, A.M.; methodology A.M. and O.S.; software, P.E.; validation, A.M. and O.S.; formal analysis, O.S.; investigation, A.M. and O.S.; resources, P.E.; data curation, A.M.; writing—original draft preparation, A.M. and O.S.; writing—review and editing, M.M.; visualization, P.E. and A.M.; supervision, O.S.; project administration, N.L.; funding acquisition, A.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by "Gubkin Russian State University of Oil and Gas" as part of the implementation of a scientific research project.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: https://disk.yandex.ru/d/OC-FVct1tvwHWQ (accessed on 27 March 2023).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Huang, C.; Wang, Y.; Li, X.; Ren, L.; Zhao, J.; Hu, Y.; Zhang, L.; Fan, G.; Xu, J.; Gu, X.; et al. Clinical features of patients infected with 2019 novel coronavirus in Wuhan, China. *Lancet* **2020**, *395*, 497–506. [CrossRef] [PubMed]
2. WHO Coronavirus (COVID-19) Dashboard. Available online: https://covid19.who.int/ (accessed on 25 February 2023).
3. Nicola, M.; Alsafi, Z.; Sohrabi, C.; Kerwan, A.; Al-Jabir, A.; Iosifidis, C.; Agha, M.; Agha, R. The socio-economic implications of the coronavirus pandemic (COVID-19): A review. *Int. J. Surg.* **2020**, *78*, 185–193. [CrossRef] [PubMed]
4. Available online: https://www.who.int/ru/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health (accessed on 27 April 2023).
5. Bao, R.; Zhang, A. Does lockdown reduce air pollution? Evidence from 44 cities in northern China. *Sci. Total Environ.* **2020**, *731*, 139052. [CrossRef]

6. He, G.; Pan, Y.; Tanaka, T. The short-term impacts of COVID-19 lockdown on urban air pollution in China. *Nat. Sustain.* **2020**, *3*, 1005–1011. [CrossRef]
7. Mahato, S.; Pal, S.; Ghosh, K.G. Effect of lockdown amid COVID-19 pandemic on air quality of the megacity Delhi, India. *Sci. Total Environ.* **2020**, *730*, 139086. [CrossRef]
8. Piccoli, A.; Agresti, V.; Balzarini, A.; Bedogni, M.; Bonanno, R.; Collino, E.; Colzi, F.; Lacavalla, M.; Lanzani, G.; Pirovano, G.; et al. Modeling the Effect of COVID-19 Lockdown on Mobility and NO_2 Concentration in the Lombardy Region. *Atmosphere* **2020**, *11*, 1319. [CrossRef]
9. List of Pollutants Subject to State Regulation Measures in the Field of Environmental Protection. Available online: https://docs.cntd.ru/document/420286994?marker=6500IL (accessed on 27 April 2023).
10. Sicard, P.; De Marco, A.; Agathokleous, E.; Feng, Z.; Xu, X.; Paoletti, E.; Rodriguez, J.J.D.; Calatayud, V. Amplified ozone pollution in cities during the COVID-19 lockdown. *Sci. Total Environ.* **2020**, *735*, 139542. [CrossRef]
11. Gautam, S. The Influence of COVID-19 on Air Quality in India: A Boon or Inutile. *Bull. Environ. Contam. Toxicol.* **2020**, *104*, 724–726. [CrossRef]
12. Resmi, C.; Nishanth, T.; Kumar, M.S.; Manoj, M.; Balachandramohan, M.; Valsaraj, K. Air quality improvement during triple-lockdown in the coastal city of Kannur, Kerala to combat COVID-19 transmission. *PeerJ* **2020**, *8*, e9642. [CrossRef]
13. Li, J.; Tartarini, F. Changes in Air Quality during the COVID-19 Lockdown in Singapore and associations with Human Mobility Trends. *Aerosol Air Qual. Res.* **2020**, *20*, 1748–1758. [CrossRef]
14. Siciliano, B.; Carvalho, G.; da Silva, C.M.; Arbilla, G. The impact of COVID-19 partial lockdown on primary pollutant concentrations in the atmosphere of Rio de Janeiro and Sao Paulo megacities (Brazil). *Bull. Environ. Contam. Toxicol.* **2020**, *105*, 2–8. [CrossRef]
15. Hudda, N.; Simon, M.C.; Patton, A.P.; Durant, J.L. Reductions in traffic-related black carbon and ultrafine particle number concentrations in an urban neighborhood during the COVID-19 pandemic. *Sci. Total Environ.* **2020**, *742*, 140931. [CrossRef]
16. Rossi, R.; Ceccato, R.; Gastaldi, M. Effect of Road Traffic on Air Pollution. Experimental Evidence from COVID-19 Lockdown. *Sustainability* **2020**, *12*, 8984. [CrossRef]
17. Collivignarelli, M.C.; De Rose, C.; Abbà, A.; Baldi, M.; Bertanza, G.; Pedrazzani, R.; Sorlini, S.; Miino, M.C. Analysis of lockdown for COVID -19 impact on NO_2 in London, Milan and Paris: What lesson can be learnt? *Process Saf. Environ. Protect.* **2021**, *146*, 952–960. [CrossRef] [PubMed]
18. Dantas, G.; Siciliano, B.; França, B.B.; da Silva, C.M.; Arbilla, G. The impact of COVID-19 partial lockdown on the air quality of the city of Rio de Janeiro, Brazil. *Sci. Total Environ.* **2020**, *729*, 139085. [CrossRef] [PubMed]
19. Le, T.; Wang, Y.; Liu, L.; Yang, J.; Yung, Y.L.; Li, G.; Seinfeld, J.H. Unexpected air pollution with marked emission reductions during the COVID-19 outbreak in China. *Science* **2020**, *369*, 702–706. [CrossRef] [PubMed]
20. Rodríguez-Urrego, D.; Rodríguez-Urrego, L. Air quality during the COVID-19: PM2.5 analysis in the 50 most polluted capital cities in the world. *Environ. Pollut.* **2020**, *266*, 115042. [CrossRef] [PubMed]
21. Venter, Z.S.; Aunan, K.; Chowdhury, S.; Lelieveld, J. COVID-19 lockdowns cause global air pollution declines. *Proc. Natl. Acad. Sci. USA* **2020**, *117*, 18984–18990. [CrossRef]
22. Skorokhod, A.I.; Rakitin, V.S.; Kirillova, N.S. Impact of COVID-19 Pandemic Preventing Measures and Meteorological Conditions on the Atmospheric Air Composition in Moscow in 2020. *Russ. Meteorol. Hydrol.* **2022**, *47*, 183–190. [CrossRef]
23. Tronin, A.; Saint Petersburg Scientific Research Center for Ecological Safety RAS; Kiselev, A.; Vasiliev, M.; Sedeeva, M.; Nerobelov, G. Monitoring NO_2 content in the atmosphere of Russia using satellite data during COVID-19 pandemic. *Curr. Probl. Remote Sens. Earth Space* **2021**, *18*, 309–313. (In Russian) [CrossRef]
24. Savin, I.Y.; Chinilin, A.V.; Avetyan, S.A.; Shishkonakova, E.A.; Prudnikova, E.Y. Satellite indicators of air quality changes over Russia due to the COVID-19 pandemic restrictions. *RUDN J. Ecol. Life Saf.* **2021**, *29*, 250–265. [CrossRef]
25. Beloconi, A.; Vounatsou, P. Long-term air pollution exposure and COVID-19 case-severity: An analysis of individual-level data from Switzerland. *Environ. Res.* **2023**, *216*, 114481. [CrossRef] [PubMed]
26. Yang, T.; Si, F.; Zhou, H.; Zhao, M.; Lin, F.; Zhu, L. Preflight Evaluation of the Environmental Trace Gases Monitoring Instrument with Nadir and Limb Modes (EMI-NL) Based on Measurements of Standard NO_2 Sample Gas. *Remote Sens.* **2022**, *14*, 5886. [CrossRef]
27. Chen, X.; Zhang, F.; Dianguo, Z.; Xu, L.; Liu, R.; Xiaomi, T.; Xin, Z.; Li, W.; Li, W. Variations of air pollutant response to COVID-19 lockdown in cities of the Tibetan Plateau. *Remote Sens.* **2023**, *3*, 708. [CrossRef]
28. Bernath, P.F.; McElroy, C.T.; Abrams, M.C.; Boone, C.D.; Butler, M.; Camy-Peyret, C.; Carleer, M.; Clerbaux, C.; Coheur, P.; Colin, R.; et al. Atmospheric Chemistry Experiment (ACE): Mission overview. *Geophys. Res. Lett.* **2005**, *32*, 5. [CrossRef]
29. Hamazaki, T.; Kaneko, Y.; Kuze, A.; Kondo, K. Fourier transform spectrometer for Greenhouse Gases Observing Satellite (GOSAT). *Enabling Sens. Platf. Technol. Spaceborne Remote Sens.* **2005**, *5659*, 73–80. [CrossRef]
30. Saito, M.; Niwa, Y.; Saeki, T.; Cong, R.; Miyauchi, T. Overview of model systems for global carbon dioxide and methane flux estimates using GOSAT and GOSAT-2 observations. *J. Remote Sens. Soc. Jpn.* **2019**, *39*, 50–56.
31. Waters, J.W.; Froidevaux, L.; Harwood, R.S.; Jarnot, R.F.; Pickett, H.M.; Read, W.G.; Siegel, P.H.; Cofield, R.E.; Filipiak, M.J.; Flower, D.; et al. The earth observing system microwave limb sounder (EOS MLS) on the aura satellite. *IEEE Trans. Geosci. Remote Sens.* **2006**, *44*, 1075–1092. [CrossRef]

32. Prunet, P.; Lezeaux, O.; Camy-Peyret, C.; Thevenon, H. Analysis of the NO_2 tropospheric product from S5P TROPOMI for monitoring pollution at city scale. *City Environ. Interact.* **2020**, *8*, 100051. [CrossRef]
33. Saw, G.K.; Dey, S.; Kaushal, H.; Lal, K. Tracking NO_2 emission from thermal power plants in North India using TROPOMI data. *Atmos. Environ.* **2021**, *259*, 118514. [CrossRef]
34. Gorelick, N.; Hancher, M.; Dixon, M.; Ilyushchenko, S.; Thau, D.; Moore, R. Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sens. Environ.* **2017**, *202*, 18–27. [CrossRef]
35. Veefkind, J.P.; Aben, I.; McMullan, K.; Förster, H.; de Vries, J.; Otter, G.; Claas, J.; Eskes, H.J.; de Haan, J.F.; Kleipool, Q.; et al. TROPOMI on the ESA Sentinel-5 Precursor: A GMES mission for global observations of the atmospheric composition for climate, air quality and ozone layer applications. *Remote Sens. Environ.* **2012**, *120*, 70–83. [CrossRef]
36. Russian Statistical Agency. The Population of the Russian Federation by Municipalities as of January 1, 2021. Available online: https://rosstat.gov.ru/compendium/document/13282 (accessed on 8 February 2021). (In Russian)
37. Yandex DataLens. Available online: https://datalens.yandex/7o7is1q6ikh23?tab=q6 (accessed on 27 April 2023).
38. Yandex Shelter-in-Place Index. Available online: https://yandex.ru/company/researches/2020/podomam (accessed on 27 April 2023).
39. Hartwell, C.A.; Otrachshenko, V.; Popova, O. Waxing power, waning pollution: The effect of COVID-19 on Russian environmental policymaking. *Ecol. Econ.* **2021**, *184*, 107003. [CrossRef]
40. National Lockdown. Russian Presidential Decree No. 206 Dated 25.03.2020. Available online: http://www.consultant.ru/document/cons_doc_LAW_348485/#:~:text=%D0%92%20%D1%86%D0%B5%D0%BB%D1%8F%D1%85%20%D0%BE%D0%B1%D0%B5%D1%81%D0%BF%D0%B5%D1%87%D0%B5%D0%BD%D0%B8%D1%8F%20%D1%81%D0%B0%D0%BD%D0%B8%D1%82%D0%B0%D1%80%D0%BD%D0%BE%2D%D1%8D%D0%BF%D0%B8%D0%B4%D0%B5%D0%BC%D0%B8%D0%BE%D0%BB%D0%BE%D0%B3%D0%B8%D1%87%D0%B5%D1%81%D0%BA%D0%BE%D0%B3%D0%BE,%D1%81%D0%BE%D1%85%D1%80%D0%B0%D0%BD%D0%B5%D0%BD%D0%B8%D0%B5%D0%BC%20%D0%B7%D0%B0%20%D1%80%D0%B0%D0%B1%D0%BE%D1%82%D0%BD%D0%B8%D0%BA%D0%B0%D0%BC%D0%B8%20%D0%B7%D0%B0%D1%80%D0%B0%D0%B1%D0%BE%D1%82%D0%BD%D0%BE%D0%B9%20%D0%BF%D0%BB%D0%B0%D1%82%D1%8B (accessed on 27 April 2023).
41. COVID-19 Public Health Initiative. Russian Presidential Decree No. 239 Dated 02.04.2020. Available online: http://www.consultant.ru/document/cons_doc_LAW_349217/#dst100008 (accessed on 27 April 2023).
42. COVID-19 Public Health Initiative Extension. Russian Presidential Decree No. 294 Dated 28.04.2020. Available online: http://www.consultant.ru/document/cons_doc_LAW_351539/ (accessed on 27 April 2023).
43. Sentinel-5P OFFL SO_2: Offline Sulfur Dioxide. Available online: https://developers.google.com/earth-engine/datasets/catalog/COPERNICUS_S5P_OFFL_L3_SO2 (accessed on 26 April 2023).
44. Abdullah, S.; Mansor, A.A.; Napi, N.N.L.M.; Mansor, W.N.W.; Ahmed, A.N.; Ismail, M.; Ramly, Z.T.A. Air quality status during 2020 Malaysia Movement Control Order (MCO) due to 2019 novel coronavirus (2019-nCoV) pandemic. *Sci. Total Environ.* **2020**, *729*, 139022. [CrossRef]
45. Cui, Y.; Ji, D.; Maenhaut, W.; Gao, W.; Zhang, R.; Wang, Y. Levels and sources of hourly PM2.5-related elements during the control period of the COVID-19 pandemic at a rural site between Beijing and Tianjin. *Sci. Total Environ.* **2020**, *744*, 140840. [CrossRef] [PubMed]
46. Bekbulat, B.; Apte, J.S.; Millet, D.B.; Robinson, A.L.; Wells, K.C.; Presto, A.A.; Marshall, J.D. Changes in criteria air pollution levels in the US before, during, and after COVID -19 stay-at-home orders: Evidence from regulatory monitors. *Sci. Total Environ.* **2021**, *769*, 144693. [CrossRef]
47. Chen, K.; Wang, M.; Huang, C.; Kinney, P.L.; Anastas, P.T. Air pollution reduction and mortality benefit during the COVID-19 outbreak in China. *Lancet Planet Health* **2020**, *4*, e210–e212. [CrossRef] [PubMed]
48. Singh, R.P.; Chauhan, A. Impact of lockdown on air quality in India during COVID-19 pandemic. *Air Qual. Atmos. Health* **2020**, *13*, 921–928. [CrossRef] [PubMed]
49. Vadrevu, K.P.; Eaturu, A.; Biswas, S.; Lasko, K.; Sahu, S.; Garg, J.K.; Justice, C. Spatial and temporal variations of air pollution over 41 cities of India during the COVID-19 lockdown period. *Sci. Rep.* **2020**, *10*, 16574. [CrossRef] [PubMed]
50. Khreis, H. Chapter Three—Traffic, Air Pollution, and Health. In *Advances in Transportation and Health*; Nieuwenhuijsen, M.J., Khreis, H., Eds.; Elsevier: Amsterdam, The Netherlands, 2020; pp. 59–104, ISBN 9780128191361. [CrossRef]
51. Singh, N.; Singh, S.; Mall, R. Chapter 17—Urban Ecology and Human Health: Implications of Urban Heat Island, Air Pollution and Climate Change Nexus. In *Urban Ecology*; Verma, P., Singh, P., Singh, R., Raghubanshi, A.S., Eds.; Elsevier: Amsterdam, The Netherlands, 2020; pp. 317–334, ISBN 9780128207307. [CrossRef]
52. Manisalidis, I.; Stavropoulou, E.; Stavropoulos, A.; Bezirtzoglou, E. Environmental and Health Impacts of Air Pollution: A Review. *Front. Public Health* **2020**, *8*, 14. [CrossRef]
53. Rodríguez, M.C.; Dupont-Courtade, L.; Oueslati, W. Air pollution and urban structure linkages: Evidence from European cities. *Renew. Sustain. Energy Rev.* **2016**, *53*, 1–9. [CrossRef]
54. Borck, R.; Schrauth, P. Population density and urban air quality. *Reg. Sci. Urban Econ.* **2020**, *86*, 103596. [CrossRef]
55. Carozzi, F.; Roth, S. Dirty density: Air quality and the density of American cities. *J. Environ. Econ. Manag.* **2023**, *118*, 102767. [CrossRef]

56. American Lung Association. Nitrogen Dioxide. Available online: https://www.lung.org/clean-air/outdoors/what-makes-air-unhealthy/nitrogen-dioxide (accessed on 27 April 2023).
57. Zhu, H.; Yang, L. Formation mechanism of NO_2 distribution heterogeneity at different spatial scales. *Resour. Environ. Sustain.* **2023**, *12*, 100106. [CrossRef]
58. Van Der A, R.J.; Eskes, H.J.; Boersma, K.F.; Van Noije, T.P.C.; Van Roozendael, M.; De Smedt, I.; Peters, D.H.M.U.; Meijer, E.W. Trends, seasonal variability and dominant NO_x source derived from a ten year record of NO_2 measured from space. *J. Geophys. Res. Atmos.* **2008**, *113*, D04302. [CrossRef]
59. Degraeuwe, B.; Thunis, P.; Clappier, A.; Weiss, M.; Lefebvre, W.; Janssen, S.; Vranckx, S. Impact of passenger car NOX emissions on urban NO_2 pollution—Scenario analysis for 8 European cities. *Atmos. Environ.* **2017**, *171*, 330–337. [CrossRef]
60. Volke, M.I.; Abarca-Del-Rio, R.; Ulloa-Tesser, C. Impact of mobility restrictions on NO_2 concentrations in key Latin American cities during the first wave of the COVID-19 pandemic. *Urban Clim.* **2023**, *48*, 101412. [CrossRef]
61. Benchrif, A.; Wheida, A.; Tahri, M.; Shubbar, R.M.; Biswas, B. Air quality during three COVID -19 lockdown phases: AQI, PM2.5 and NO_2 assessment in cities with more than 1 million inhabitants. *Sustain. Cities Soc.* **2021**, *74*, 103170. [CrossRef]
62. Wyche, K.; Nichols, M.; Parfitt, H.; Beckett, P.; Gregg, D.; Smallbone, K.; Monks, P. Changes in ambient air quality and atmospheric composition and reactivity in the South East of the UK as a result of the COVID-19 lockdown. *Sci. Total Environ.* **2020**, *755*, 142526. [CrossRef]
63. Zhang, Q.; Pan, Y.; He, Y.; Walters, W.W.; Ni, Q.; Liu, X.; Xu, G.; Shao, J.; Jiang, C. Substantial nitrogen oxides emission reduction from China due to COVID-19 and its impact on surface ozone and aerosol pollution. *Sci. Total Environ.* **2020**, *753*, 142238. [CrossRef]
64. McDuffie, E.E.; Smith, S.J.; O'Rourke, P.; Tibrewal, K.; Venkataraman, C.; Marais, E.A.; Zheng, B.; Crippa, M.; Brauer, M.; Martin, R.V. A global anthropogenic emission inventory of atmospheric pollutants from sector- and fuel-specific sources (1970–2017): An application of the Community Emissions Data System (CEDS). *Earth Syst. Sci. Data* **2020**, *12*, 3413–3442. [CrossRef]
65. Jiang, L.; He, S.; Cui, Y.; Zhou, H.; Kong, H. Effects of the socio-economic influencing factors on SO_2 pollution in Chinese cities: A spatial econometric analysis based on satellite observed data. *J. Environ. Manag.* **2020**, *268*, 110667. [CrossRef]
66. Madkour, K.M. Monitoring the impacts of COVID-19 pandemic on climate change and the environment on Egypt using Sentinel-5P Images, and the Carbon footprint methodology. *Egypt. J. Remote Sens. Space Sci.* **2022**, *25*, 205–219. Available online: https://www.sciencedirect.com/science/article/pii/S1110982321000508 (accessed on 26 April 2023).
67. Ghasempour, F.; Sekertekin, A.; Kutoglu, S.H. Google Earth Engine based spatio-temporal analysis of air pollutants before and during the first wave COVID-19 outbreak over Turkey via remote sensing. *J. Clean. Prod.* **2021**, *319*, 128599. [CrossRef]
68. Kovács, K.D.; Haidu, I. Effect of Anti-COVID-19 Measures on Atmospheric Pollutants Correlated with the Economies of Medium-sized Cities in 10 Urban Areas of Grand Est Region, France. *Sustain. Cities Soc.* **2021**, *74*, 103173. [CrossRef]
69. Stationary Source Emissions (Federal Service for Supervision of Natural Resources). Available online: https://rpn.gov.ru/open-service/analytic-data/statistic-reports/air-protect/ (accessed on 27 April 2023).
70. OKVED2 Production Index (Real-Time). Available online: https://showdata.gks.ru/report/274128 (accessed on 27 April 2023).
71. Sannigrahi, S.; Kumar, P.; Molter, A.; Zhang, Q.; Basu, B.; Basu, A.S.; Pilla, F. Examining the status of improved air quality in world cities due to COVID-19 led temporary reduction in anthropogenic emissions. *Environ. Res.* **2021**, *196*, 110927. [CrossRef] [PubMed]
72. Barré, J.; Petetin, H.; Colette, A.; Guevara, M.; Peuch, V.-H.; Rouil, L.; Engelen, R.; Inness, A.; Flemming, J.; Pérez García-Pando, C.; et al. Estimating lock-down-induced European NO_2 changes using satellite and surface observations and air quality models. *Atmos. Chem. Phys.* **2021**, *21*, 7373–7394. [CrossRef]
73. Bar, S.; Parida, B.R.; Mandal, S.P.; Pandey, A.C.; Kumar, N.; Mishra, B. Impacts of partial to complete COVID-19 lockdown on NO_2 and PM2.5 levels in major urban cities of Europe and USA. *Cities* **2021**, *117*, 103308. [CrossRef]
74. Habiboğlu, O.; Çelik, Z.; Bölükbasi, Y. Research of Consumers' Online Shopping Attitudes and Intentions, Based on Fear of Coronavirus (COVID-19) and Death Anxiety. In Proceedings of the 3rd International Conference on Innovative Studies of Contemporary Sciences, Tokyo, Japan, 19–21 February 2021.
75. Webb, A.; McQuaid, R.W.; Webster, C.W.R. Moving learning online and the COVID-19 pandemic: A university response. *World J. Sci. Technol. Sustain. Dev.* **2021**, *18*, 1–19. [CrossRef]
76. NAFI and Logitech: Most Employees Want to Work 2–3 Days a Week from Home. Available online: https://nafi.ru/analytics/issledovanie-gibridnogo-formata-raboty-nafi-i-logitech-bolshinstvo-sotrudnikov-khotyat-rabotat-2-3-d/ (accessed on 27 April 2023).
77. Remote Work Is Back, but So Far on a Smaller Scale. Available online: https://www.superjob.ru/research/articles/113689/udalenka-vozvraschaetsya/ (accessed on 27 April 2023).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.