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# Assessing air quality changes in large cities during COVID-19 lockdowns: The impacts of traffic-free urban conditions in Almaty, Kazakhstan

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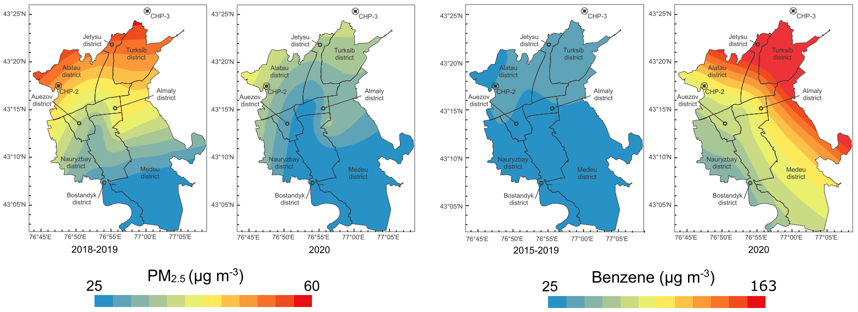
## HIGHLIGHTS

- $PM_{2.5}$ concentration reduced by 21% with spatial variations of 6–34% compared to the average of the same days in 2018–2019
- CO and $NO_2$ concentrations reduced by 49% and 35%, respectively
- $O_3$ concentrations increased by 15% compared to the preceding 17 days before the lockdown
- Concentrations of benzene and toluene were 2–3 times higher than in the same seasons of 2015–2019.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Number of cities worlwide experienced air quality improvements during COVID-19 lockdowns; however, such changes may have been different in places with major contributions from nontraffic related sources. In Almaty, a city-scale quarantine came into force on March 19, 2020, which was a week after the first COVID-19 case was registered in Kazakhstan. This study aims to analyze the effect of the lockdown from March 19 to April 14, 2020 (27 days), on the concentrations of air pollutants in Almaty. Daily concentrations of $PM_{2.5}$, $NO_2$, $SO_2$, CO, $O_3$, and BTEX were compared between the periods before and during the lockdown. During the lockdown, the $PM_{2.5}$ concentration was reduced by 21% with spatial variations of 6–34% compared to the average on the same days in 2018–2019, and still, it exceeded WHO daily limit values for 18 days. There were also substantial reductions in CO and $NO_2$ concentrations by 49% and 35%, respectively, but an increase in $O_3$ levels by 15% compared to the prior 17 days before the lockdown. The concentrations of benzene and toluene were 2–3 times higher than those during in the same seasons of 2015–2019. The temporal reductions may not be directly attributed to the lockdown due to favorable meteorological variations during the period, but the spatial effects of the quarantine on the pollution levels are evidenced. The results demonstrate the impact of traffic on the complex nature of air pollution in Almaty, which is substantially contributed by various nontraffic related sources, mainly coal-fired combined heat and power plants

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and household heating systems, as well as possible small irregular sources such as garbage burning and bathhouses.

## 1. Introduction

The first case of SARS-CoV-2 infection was registered in Kazakhstan on March 13, 2020. Learning from the experience of other countries, the reaction of authorities was fast. On March 16, 2020, an emergency situation was declared, and beginning on March 19, 2020, a city-scale quarantine or "lockdown" was introduced for the whole city of Almaty. Limits on entry and exit in the city were applied (with the exception of cargo trucks for vital purposes). Since March 28, more restrictive measures were introduced, and residents of Almaty could leave their homes only for grocery shopping and work (only with special permission). Since March 30, 2020, all organizations and enterprises were temporarily suspended, with a gradual staged opening of some selected industries expected in late April and in May. Such measures resulted in nearly absent of road traffic, while at the same time, coal-fired combined heat and power plants (CHPs) were continuously operating. Air quality changes due to the COVID-19 lockdowns quickly became a new topic of recent research studies. Decreases in nitrogen dioxide levels ($NO_2$) over China during February 10–25 (during quarantine) compared to January 1–20, 2020 (before quarantine) were identified using satellite data from NASA and the European Space Agency (ESA) (Earth Observatory, 2020). (Tobías et al., 2020) also depicted substantial air quality improvements after two weeks of lockdown in Barcelona (Spain). The results support the idea that air pollution could be substantially improved in cities where transport was a major source. However, the air quality improvements during COVID-19 lockdowns may not clearly favor improving the air quality in areas with a more complex mix of sources, where transport emissions have minor impacts compared to emissions from other sources (e.g., coal combustion for power and heating).

Concerning the levels of BTEX, Almaty is among the most polluted cities in the world (Carlsen et al., 2018). In terms of priority pollutants, it is one of the most polluted cities of Kazakhstan (Kerimray et al., 2019), and there were 21 days in 2018 on which the $PM_{2.5}$ concentrations exceeded 250 $\mu g\ m^{-3}$ at least at one station (Kerimray et al., 2020). The wintertime concentrations of major atmospheric air pollutants were several times higher than those during summertime, which could be explained by intensive coal combustion at power plants and in households for heating. Two coal-fired combined heat and power plants named "CHP-2" and "CHP-3" annually burn approximately 2.2 million tons (Department of Ecology of Almaty, 2015) and 950 thousand tons (Department of Ecology of Almaty region, 2015) of low-grade coal with a high ash content (approximately 35–40%), respectively, and they are not equipped with proper emissions control systems (e.g., electrostatic precipitators or desulfurization units). Emissions from coal-fired power plants exceeded the limit values for power plants in Europe by 10 times for PM, 20% for $NO_x$, and 2.5 times for $SO_x$ (Ministry of Environmental Protection of Republic of Kazakhstan, 2013).

However, the municipality of Almaty declared that the main source of air pollution was motor vehicles in 2016, as the corresponding sum of emissions accounted for 79,486 tons, while stationary sources accounted only for 38,779 tons. This approach of summing all pollutant emissions led to a distorted estimation of the inputs from different sources, and civil activists and scientists largely criticized it. In February 2020, >20,000 citizens signed an online petition urging officials to acknowledge the coal-fired power plants as the main emitters in Almaty (Vlast, 2020). The inappropriate identification of the inventory is caused not only by the lack of capacity and outdated methodologies but also by the scarcity of data and nontransparent energy statistics (Kerimray et al., 2017). Since the data on fuel consumption and emissions are not publicly available, producing independent inventories of pollutants is a complicated task. Source apportionment with chemical analysis of PM particles is needed; however, due to the scarcity of funding for expensive laboratory equipment and the lack of capacity, it has not been conducted so far.

In this study, changes in the air quality before and during the period of COVID-19 lockdown in Almaty were quantified. The possible effects of traffic emissions were discussed. Daily concentrations of $PM_{2.5}$, $NO_2$, $SO_2$, CO, and $O_3$ were compared between the periods before (e.g., during the preceding three weeks or the same days in earlier years) and during the lockdown. Benzene, toluene, ethylbenzene, and *o*-xylene (BTEX) concentrations were also measured during three days in the middle of the lockdown and compared with the concentrations observed during the same periods of previous years (2015–2019). This study aims to assess the impacts of COVID-19 lockdown conditions (traffic-free) on the air quality of Almaty, which is one of the most polluted large cities in the world.

## 2. Methodology

In this study, daily $PM_{2.5}$ concentration levels were obtained from the "Airkaz" public air quality monitoring network (www.airkaz.org), which uses Pms5003 $PM_{2.5}$ sensors (Plantower, China) to measure the concentrations of $PM_{2.5}$ every minute. Seven (7) stations (https://goo.gl/maps/6UPRmjJoYpwEg2D56) of a total of 31 stations on the network were selected for this study since only these stations had a full dataset for the targeted dates and periods. None of the selected stations was located close to CHP-2 since the station close to CHP-2 did not record full data for March. $PM_{2.5}$ concentrations were compared between the lockdown period during March 19 to April 14, 2020, and the same period in previous years. Additionally, the air quality was compared within 2020 between the periods before lockdown (February 21 – March 18) and during lockdown (March 19 – April 14).

Monitoring of benzene, toluene, ethylbenzene, and *o*-xylene (BTEX) was conducted every spring at 8 AM and 8 PM at six different locations (https://goo.gl/maps/6UPRmjJoYpwEg2D56) during the period from the end of March to the beginning of April from 2015 to 2020. The sampling and analysis methods developed by (Baimatova et al., 2016) and (Ibragimova et al., 2019) were followed. The lockdown BTEX sampling was conducted on three days in the middle of the lockdown.

Daily $NO_2$, $O_3$, $SO_2$, and CO concentration values for the period of March 2 – April 14, 2020, from one station (located in the city center) were obtained from the "Skymax Technologies" company. $NO_2$, $O_3$, $SO_2$, and CO concentration values were not available for the previous years.

The wind speed, wind direction, temperature, relative humidity, precipitation were obtained from the http://rp5.kz website (Weather Schedule, 2020), which collects data from the National Oceanic and Atmospheric Administration (USA) from the station located at 43.15°N, 76.57°E at an elevation of 848 m above sea level.

The cokriging method utilized in the ArcGIS® Geostatistical Analyst tool (https://desktop.arcgis.com/ru/arcmap/) was used to map $PM_{2.5}$ and benzene distributions across Almaty in 2018–2019 and 2020, respectively. The digital elevation model (DEM) of Almaty from the Shuttle Radar Topography Mission (SRTM) data was used as a secondary dataset. Ordinary cokriging was used to build the map with the first order of trend removal for the primary dataset and local polynomial interpolation, as in all cases, the data had a trend in distribution.

**Table 1**
Meteorological conditions for the preceding days (February 21–March 18), and the lockdown days (March 19–April 14).

| | Temperature (°C) | | Relative humidity (%) | | Wind speed (m $s^{-1}$) | | Precipitation (mm) | |
|---|---|---|---|---|---|---|---|---|
| | Average | SD | Average | SD | Average | SD | Average | SD |
| February 21 – March 18 | | | | | | | | |
| 2018 | 4.7 | 3.8 | 73.9 | 15.2 | 0.3 | 0.1 | 5.5 | 3.3 |
| 2019 | 4.6 | 4.5 | 66.5 | 16.5 | 0.3 | 0.2 | 3.5 | 2.3 |
| 2020 | 5.5 | 5.4 | 62.4 | 17.4 | 0.4 | 0.3 | 3.3 | 3.5 |
| March 19 – April 14 | | | | | | | | |
| 2018 | 11.2 | 4.2 | 60.3 | 14.9 | 0.4 | 0.2 | 5.5 | 4.2 |
| 2019 | 11.6 | 3.2 | 63.5 | 13.3 | 0.4 | 0.2 | 4.5 | 4.9 |
| 2020 | 8.7 | 4.7 | 66.1 | 16.4 | 0.4 | 0.2 | 5.2 | 4.9 |

### *2.1. Meteorological conditions*

Significant temperature variations in the region characterize the transitional period from February to April. Detailed information on the meteorological factors during the selected periods are summarized in Table 1. The period between February 21 to April 14, 2020 was characterized by a substantial difference (23.3 °C) between the minimum daily temperature (−6 °C) and the maximum daily temperature (17.3 °C). The average temperature before lockdown was 5.5 °C, while it was 8.7 °C during lockdown. Additionally, there were less frequent rains before lockdown period (9 days out of 27) compared to the lockdown period (16 days out of 27). These results show that the meteorological conditions were in favor of air pollution reductions during the lockdown period compared to the preceding days.

On the other hand, the meteorological conditions during the lockdown were almost similar to those of the same periods in the previous years of 2018 and 2019 (Table 1; Fig. S1, Supplementary file). The numbers of rainy days were 15, 16, and 16 days, and the average temperatures were 11.2, 11.6, and 8.7 °C in 2018, 2019, and 2020, respectively. The lockdown period was slightly colder compared to previous years, as there were six days during the lockdown period when the daily average temperature was below 5 °C, while such temperature falls were observed only on one day in 2018 and two days in 2019. These results show that the lockdown period had slightly unfavorable meteorological conditions for air pollution compared to the earlier years.

## 3. Results and discussion

### *3.1. Impact of the lockdown on the $PM_{2.5}$ concentration*

#### *3.1.1. Effect of meteorology*

The study under analysis (February to April) is a transitional period characterized by rising temperatures and subsequent declining coal combustion by private houses (heating purposes) and CHPs. For example, the monthly coal combustion at CHP-2 shows significantly varying levels throughout the year (seasonality), with twice lower values in June compared to January and 8–15% lower values in March compared to February (Letter to the Public Council of the city of Almaty, 2020). In parallel, the average $PM_{2.5}$ concentration generally had a declining trend from February to April, even in the previous years before lockdown, with 28, 39 and 29% declines during the period March 19 – April 14 compared to the preceding days (February 21 – March 18) in 2018, 2019 and 2020, respectively (Table 2; Fig. 1). Thus, the effect of the lockdown, which started on March 19, 2020, on the average concentration change is not evident if such a decline in $PM_{2.5}$ happens annually as a result of temperature change, and this decline was the same as in the previous years without a lockdown (2018 and 2019). Thus, the reduction of the $PM_{2.5}$ concentration during the lockdown period of March 19 – April 14, 2020, compared to that during the preceding period of February 21 – March 18, 2020, can be possibly attributed to the more frequent rains, increasing temperatures, lower frequency of temperature inversions, increasing wind speeds and changes in its direction. The sharp reductions of the $PM_{2.5}$ concentration on March 22, April 2, April 9, and April 14 (2020) can be associated with rains on those days (Fig. 1).

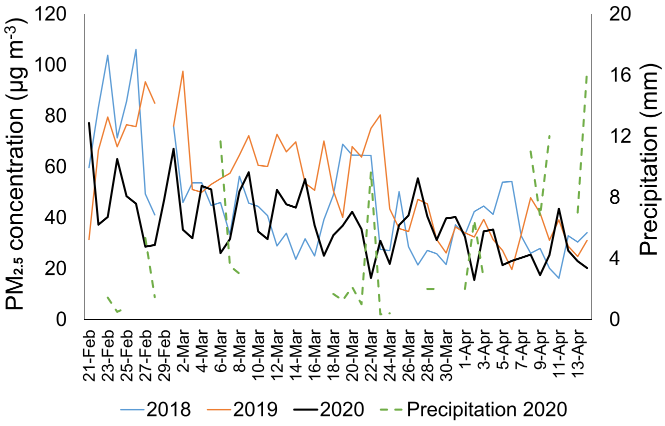

**Fig. 1.** Daily concentrations (averaged for 7 stations), μg $m^{-3}$ for three years between February 21 and April 14.

Additionally, the "before lockdown" period was characterized by a lower average concentration (44 μg $m^{-3}$) in 2020 compared to the same period in the previous years of 2018 and 2019 (53–66 μg $m^{-3}$). This record needs further investigation to better understand whether the effect is from policies and measures will last over the years. One possible (alternative) explanation could be the slightly higher temperatures during the period of February 21 – March 18 in 2020 (5.5 °C) compared to previous years (4.6–4.7 °C).

In this study, to exclude the "temperature effect" and "precipitation effect" and to explore only the effect of the lockdown, the concentrations during the same period (March 19 – April 14) of 2018, 2019, and 2020 were compared. The $PM_{2.5}$ concentrations (averaged for all stations) during the lockdown period were 38, 40, and 31 μg $m^{-3}$ in 2018, 2019 and 2020, respectively, indicating a reduction of the $PM_{2.5}$ concentration by 18% and 23% in 2020 (during lockdown) compared to the same periods in 2018 and 2019 (before the lockdown year). Fig. 1 shows that the trend of the daily $PM_{2.5}$ was fluctuating during the period of March–April in all three years, with no clear downward/upward trend between days or between years.

#### *3.1.2. Spatial differences*

The $PM_{2.5}$ concentration levels varied across the stations during the lockdown from 27 to 38 μg $m^{-3}$. The spatial reductions varied between 6% and 34% during the lockdown period compared to the other years

**Table 2**
Average $PM_{2.5}$ concentrations in the periods between February 21 and March 18, and between March 19 and April 14 in 2018–2020.

| Year | February 21 –March 18 | | March 19 –April 14 | | Percent change |
|---|---|---|---|---|---|
| | Average | SD | Average | SD | |
| 2018 | 53 | 22 | 38 | 15 | −28% |
| 2019 | 66 | 15 | 40 | 15 | −39% |
| 2020 | 44 | 13 | 31 | 10 | −29% |

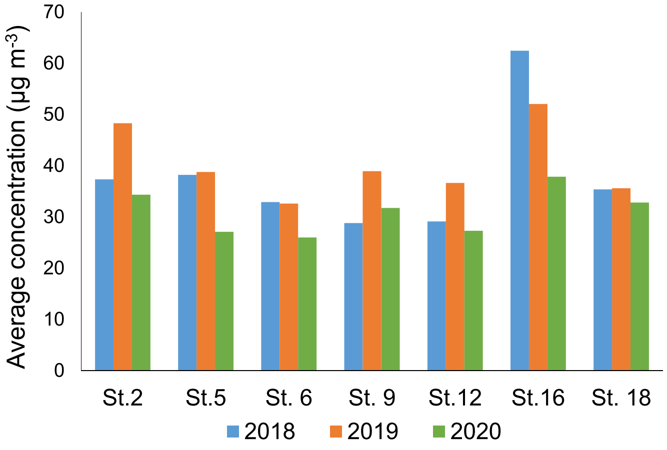

**Fig. 2.** Average concentrations of $PM_{2.5}$ in the period between March 19 and April 14.

(Figs. 2, 3 and S2, Supplementary file), and this might be attributed to the removal of traffic emissions with their varying contributions to the spatial locations. Almaty is located at an altitude between 600 m and 1300 m due to its proximity to the mountains. A previous study by (Kerimray et al., 2020) depicted that the $PM_{2.5}$ concentration was correlated with the elevations of the monitoring stations ($R^2 = 0.64$). In this study, $PM_{2.5}$ concentration levels during the 2020 lockdown did not have a correlation with the elevation ($R^2 = 0.23$), distance to CHP-2 ($R^2 = 0.1$), or distance to CHP-3 ($R^2 = 0.22$) (Fig. S2, Supplementary file). A previous study by (Kerimray et al., 2020) used data from 11 monitoring stations for $PM_{2.5}$, while in this study, data from only 7 stations was used (due to the absence of full datasets for March months in 2018–2020). However, the spatial model results shown in Fig. 3 show that the spatial profiles have similarities—lower levels in the south and higher levels in the north—but their variation ranges are significantly different. The weak correlations with distance to CHP-2 ($R^2 = 0.10$) and CHP-3 ($R^2 = 0.22$) could be due to many contributing factors, including the long distance of the sampling sites from CHP-2, several contributing sources of emissions located at different places, complicated topography, and varying wind directions.

Station 16 is the most polluted place and experienced the most significant reduction in the lockdown period from the average of 57 μg $m^{-3}$ in 2018–2019 to 38 μg $m^{-3}$ in 2020 (34% decline). Station 16 is at the lowest elevation above sea level (647 m) compared to the locations of the other stations. This station is located at the border of Almaty and administratively belongs to the Almaty region; however, it was included in this study. Station 16 is only 2.5 km away from the coal-fired CHP-3 and is located near major roads. The impacts of traffic and CHP-3 emissions are evident at this location (Kerimray et al., 2020). The high levels despite the absence of the traffic contribution (38 μg $m^{-3}$) demonstrate that coal combustion (especially close location to CHP-3) is the primary source impacting the station. Station 5, on the other hand, which is located in the city center with high traffic and a lower elevation (793 m), experienced a 30% reduction. Station 9 and Station 18 experienced only 6 and 8% reductions, respectively. Station 18 is located at the southwestern border of Almaty (administratively belongs to the Almaty region) at the elevation of 904 m. This area is mainly one- and two-story residential buildings. Station 12 is located in the southeastern part of Almaty at the highest elevation of 1348 m and is close to the mountains, and it is far away from the densely populated areas with high traffic loads. These results confirm that the city has experienced spatial $PM_{2.5}$ reductions during the lockdown period.

The number of days exceeding the daily WHO limit (25 μg $m^{-3}$) was 23, 25, and 18 days in 2018, 2019, and 2020, respectively (for the period of March 19 – April 14) (Fig. 1). The lockdown in 2020 has resulted in a 25% reduction in the number of days compared to 2018 and 2019. However, even with a traffic-free environment, WHO daily limit values in Almaty were still not met on 18 out of 27 days of the lockdown.

### 3.2. BTEX concentration analysis

The average concentrations of BTEX analytes from 2015 to 2020 are illustrated in Fig. 4. The averages for benzene (101 μg $m^{-3}$) and toluene (67 μg $m^{-3}$) were 3 and 2 times higher, while those for ethylbenzene (1.0 μg $m^{-3}$) and *o*-xylene (1.6 μg $m^{-3}$) were 4 and 2.7 times lower in 2020 than during the same sampling period in 2015–2019 (Table 3). In addition, the average concentration of benzene was 15% higher in January 2020 compared to the lockdown period.

#### 3.2.1. Differences in meteorology

The sampling period during the lockdown in April 2020 was characterized by warmer temperatures ranging from 10.2 to 16.2 °C, while the

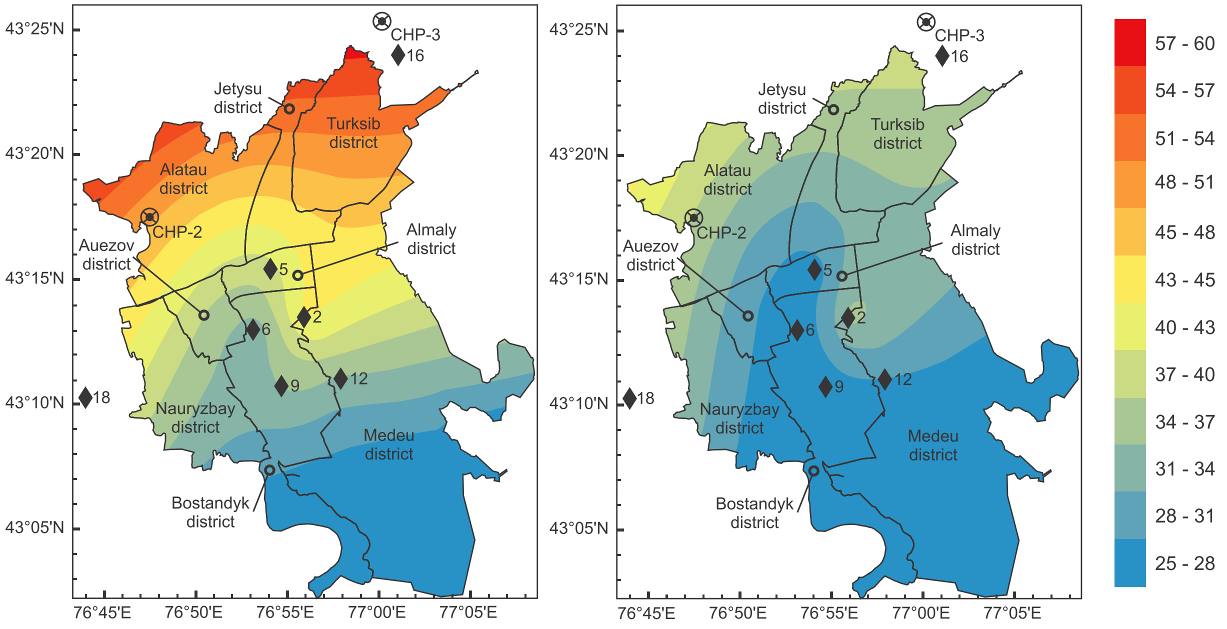

**Fig. 3.** Spatial distribution of $PM_{2.5}$ concentration between March 19 to April 14 in (2018–2019) (left) and 2020 (right).

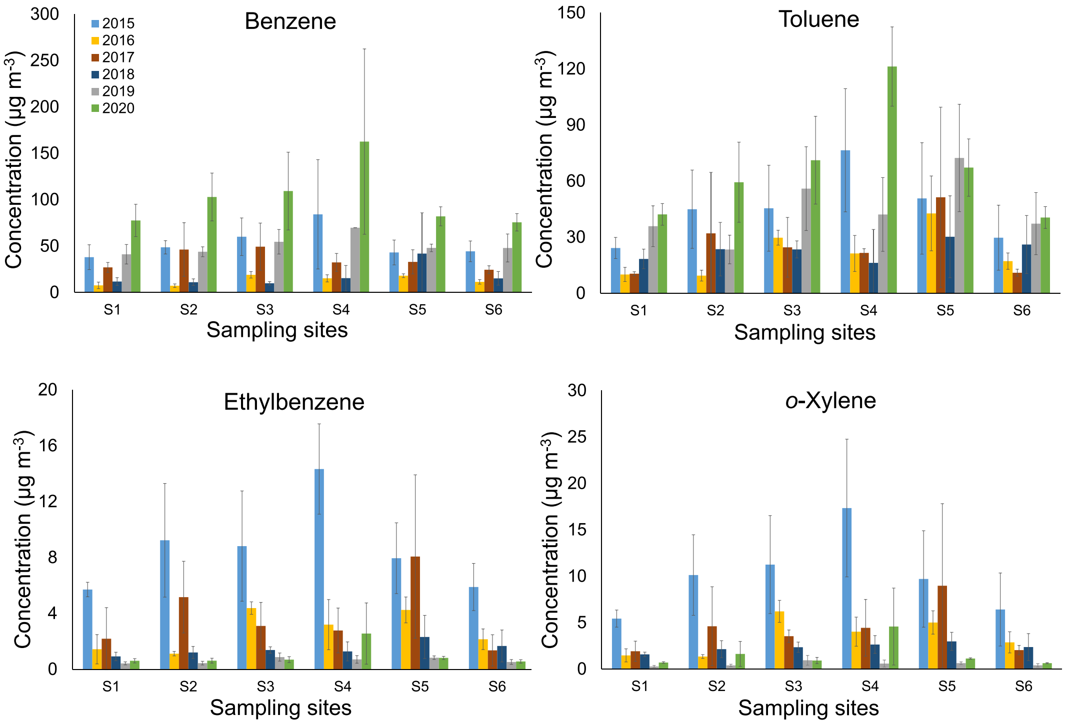

**Fig. 4.** Average ambient concentrations of BTEX from 2015 to 2020 (single measurements during three days in March and April) in Almaty.

temperature ranged from −6.2 to 14.5 °C on the sampling days in 2015–2019 (Fig. S1 and Table S1, Supplementary file). The average temperature was 14.0 °C in 2020 and 7.1 °C in 2015–2019. Wind speeds during the sampling period in 2015–2020 were similar and ranged from 0 to 1 m s$^{-1}$.

One of the reasons for the increased concentrations of benzene and toluene during the sampling days in 2020 could be attributed to the no-precipitation conditions. Since there was no traffic activity during the lockdown, the higher levels of benzene and toluene may indicate that their origins are predominantly nontraffic sources, and the declining levels of ethylbenzene and *o*-xylene by up to 3 fold could be linked to the traffic-free conditions.

### 3.2.2. Spatial differences

BTEX concentrations were inversely proportional to the elevation (above the sea level) of the sampling sites (Fig. 5) which was similar to the case for $PM_{2.5}$ concentrations. At the higher elevations (closer to the mountains), the concentrations of BTEX were lower than those at the lower elevations (Fig. 5), and this could be explained by the location of the coal-fired power plants and households burning coal at the lower elevations.

The BTEX concentrations in 2020 were inversely correlated with the distance to CHP-3, with $R^2 = 0.87$ for benzene and $R^2 = 0.82$ for toluene. The distance–concentration correlations for CHP-2 were weak ($R^2 < 0.1$), which could be due to the large distances of sampling sites from CHP-2 (Fig. S4, Supplementary file). The correlation of the benzene and toluene concentrations with the distance from CHP-3 was stronger than the correlation with the elevation (Fig. 5), and this may indicate the dominant contribution of CHP-3 to BTEX pollution in the city. According to the environmental reports of CHP-3 in 2015, coal consumption at CHP-3 was expected to increase in the future due to the rising demand for electricity (Department of Ecology of Almaty region, 2015).

**Table 3**
Percent change of BTEX concentrations during three days of spring 2020 lockdown compared to the average concentrations detected in the same periods of 2015–2019.

| Analyte | S1 | S2 | S3 | S4 | S5 | S6 | Average |
|---|---|---|---|---|---|---|---|
| Benzene | 209% | 227% | 183% | 274% | 123% | 164% | 199% |
| Toluene | 113% | 123% | 99% | 241% | 36% | 67% | 110% |
| Ethylbenzene | −72% | −82% | −81% | −43% | −83% | −76% | −72% |
| *o*-Xylene | −67% | −56% | −81% | −21% | −79% | −77% | −61% |

There were substantial increases in benzene and toluene during the lockdown period compared to the average during the 2015–2019 years, while some reductions were observed in ethylbenzene and *o*-xylene concentrations. The variations were significant and ranged between 123% and 227% for benzene and between 36% and 241% for toluene. The highest increases in the concentrations were observed at Station S4, which were 274% (by 119 µg m$^{-3}$) for benzene and 241% (by 86 µg m$^{-3}$) for toluene (Table 3). Station S4 is located at a low elevation (700 m), close to coal-burning housing developments and at the distances of 12 km from CHP-2 (Fig. S4, Supplemental materials) and 14 km from CHP-3 (Fig. 5). There is also an Almaty bus fleet park located 2.6 km away, and the public bus service was still in operation during the lockdown. The burning of coal at residential houses could have been higher, as people remained in their homes all the time during the 2020 lockdown, and there are plenty of nearby public bathhouses (saunas) that are often heated by burning their garbage or coal. On one of the sampling days, a bonfire was also observed.

Relatively lower concentrations of benzene (76–78 µg m$^{-3}$) and toluene (41–42 µg m$^{-3}$) during the 2020 lockdown were observed at sites S1 (978 m) and S6 (803 m). Sampling site S1 is located in the upper part of Almaty (closer to the mountains), while site S6 is located in a public park at 803 m above sea level. Sampling sites S3 (764 m) and S5 (770 m) are located near significant roads; however, the high levels of BTEX at sites S3 and S5 during the 2020 lockdown indicate the significant contribution from coal combustion (Fig. 6).

### 3.2.3. Identification of BTEX emission sources

The toluene-to-benzene concentration ratio (T/B) is often used in BTEX source apportionment studies (Zhang et al., 2016, 2020). The content of toluene in gasoline and exhaust gases is 3–4-fold higher than the

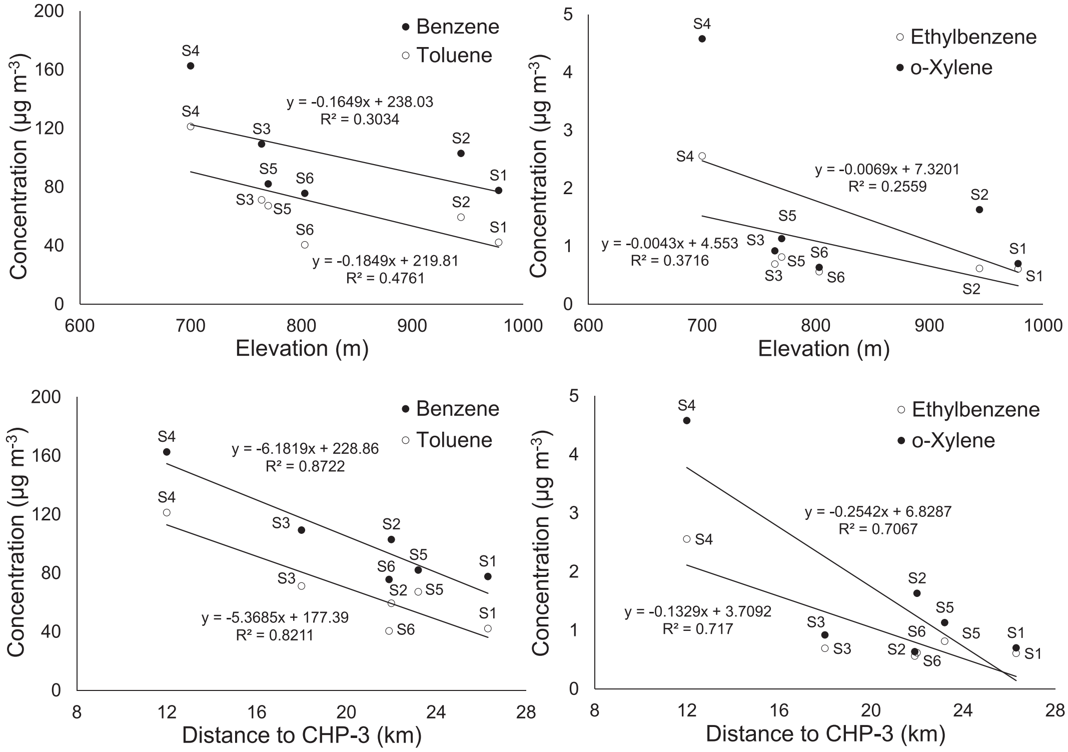

**Fig. 5.** Measured BTEX concentrations and elevation above sea level; and distance to CHP-3.

benzene content (Brocco et al., 1997). T/B ratios <1 indicate that the primary source of BTEX is biomass, biofuel, or coal burning, while T/B > 1 indicates that it mainly originates from vehicle emissions (Liu et al., 2015).

The varying T/B observed during 2015–2019 indicated the complex nature of BTEX in the ambient air of Almaty (Fig. 7). In 2015, the obtained T/B ratios were <1 in 18 out of 36 measurements, indicating that sources of BTEX were both vehicle exhaust and coal combustion (Baimatova et al., 2016). The T/B found in most of the analyzed samples in 2016 (30 from 36 measurements) and 2018 (31 from 35 measurements) were ≥1, suggesting that BTEX mainly originated from transport-related sources. The T/B of the vast majority of collected samples in 2017 (33 from 36 measurements) and 2019 (23 from 35 measurements) were <1, which indicated that BTEX mainly originated from coal burning (Ibragimova et al., 2019).

Though there were higher concentrations of toluene and benzene, the T/B ratios were below 1 in most (32 of 36) measurements, indicating the minor effect of traffic emissions during the 2020 lockdown. Three

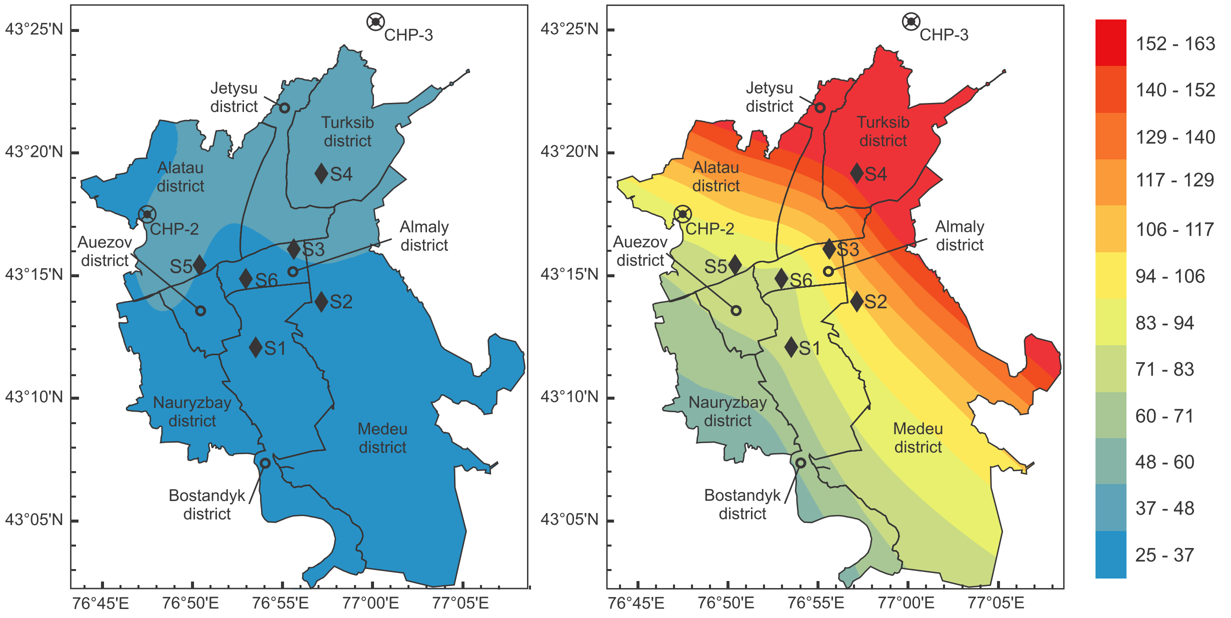

**Fig. 6.** Estimated average concentration of benzene in three days of spring in 2015–2019 (left) and 2020 (right), μg m$^{-3}$.

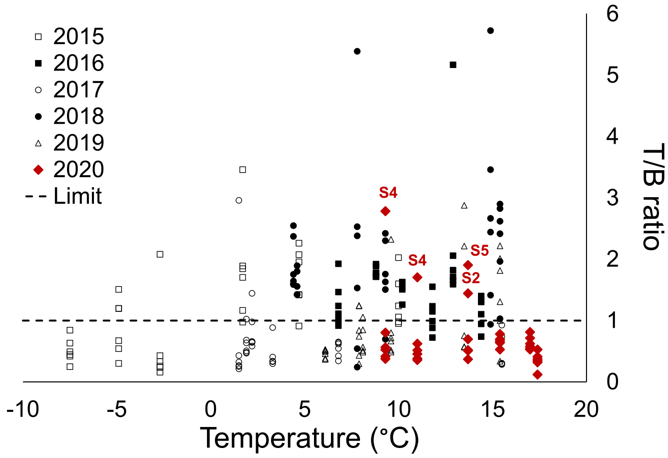

**Fig. 7.** Toluene-to-benzene ratios (T/B) in ambient air during sampling periods in March–April of 2015–2020 (single measurements) in Almaty.

measurements at sampling sites S2, S4, and S5 resulted in T/B values of >1, and one measurement at sampling site S4 showed T/B > 2. The results indicate that BTEX mostly originated from coal combustion (e.g., power plants and private houses) during the lockdown.

### *3.3. Concentrations of $NO_2$, $O_3$, $SO_2$ and CO*

The concentrations of $NO_2$, $O_3$, $SO_2$, and CO were not available from the used sources for the previous years; therefore, the values were compared between the periods before the lockdown (March 2 – March 18, 2020) and during the lockdown (March 19 – April 14, 2020) (Fig. S5, Supplementary file). There was a substantial reduction in the concentrations of CO and $NO_2$ by 49% and 35%, respectively, compared to the period before the lockdown (Table 4). The $NO_2$ and CO concentrations correlated well ($R^2 = 0.52$, Fig. S6, Supplementary file), which could indicate that CO and $NO_2$ originated from common sources (e.g., transport). The sharp reductions in $NO_2$ and CO concentrations on March 19, 22, and 28 and April 2, 8, and 14 could be partially associated with rains on those days. Thus, it is challenging to evaluate the effect of the lockdown exclusively because of the more frequent rains during the lockdown (59% of days were rainy) compared to the days before lockdown (23% of days were rainy). According to the National Hydrometeorological Service of Kazakhstan, the monthly average concentrations of $SO_2$, CO, and $NO_2$ were declining every year in April–March compared to February in the years of 2016–2019 (Kazhydromet, 2019). Data for the same period in several years has to be compared; however, it could not be done in this study due to the unavailability of data on the daily average concentrations of $NO_2$, $O_3$, $SO_2$, and CO for the recent years.

There was an increase in $O_3$ by 15%, which can be explained by the higher levels of solar activity during the period of the lockdown, while the $SO_2$ concentration increased only by 7%, which was statistically insignificant. This result depicts that traffic emissions did not influence $SO_2$ levels and that it was contributed by coal combustion.

**Table 4**
Average concentrations (μg $m^{-3}$) in the period between March 2 and April 14, 2020.

| Time period | $NO_2$ | | $SO_2$ | | CO | | $O_3$ | |
|---|---|---|---|---|---|---|---|---|
| | Average | SD | Average | SD | Average | SD | Average | SD |
| March 2–March 18 | 37 | 13 | 49 | 12 | 674 | 255 | 30 | 19 |
| March 19–April 14 | 24 | 12 | 52 | 16 | 343 | 158 | 34 | 19 |
| Percent reduction | −35% | | 7% | | −49% | | 15% | |

## 4. Conclusions

Every year, the air quality in Almaty improves gradually from February to April due to seasonal changes in the temperature and precipitation, as well as due to a subsequent reduction of coal use at the combined heat and power plants and in individual houses. Therefore, it was not reliable to perform a temporal analysis and attribute the temporal reductions to the traffic-free conditions. As an alternative method to eliminate the weather impact, the same period was compared with that during the previous years.

There was a reduction in the $PM_{2.5}$ concentration by 21% in 2020 (during lockdown) compared to the same period in 2018–2019 (before lockdown), with substantial spatial variations. Although there was a 30–34% reduction in $PM_{2.5}$ concentrations at the stations located at the lower elevations, the air was still far from being clean at those locations. Even under the low-traffic conditions in Almaty, the $PM_{2.5}$ concentrations on 18 days of the lockdown period (out of total 27 days) exceeded the WHO daily limit values, providing evidence of the high contribution from nontraffic related sources.

The substantial reductions in CO and $NO_2$ concentrations during the COVID-19 lockdown period compared to the 17 days before the lockdown could be due to the combination of traffic elimination and seasonal weather changes. Highly elevated concentrations of benzene and toluene on three sampling days during the lockdown (101 and 67 μg $m^{-3}$) and the toluene-to-benzene ratios suggest that these compounds originated from coal-related sources such as power plants and households and to possible episodic cases of garbage burning, bathhouses, and bus fleet stations.

This research demonstrates the complicated nature of air pollution in Almaty, which urgently needs further investigation through spatial inventories and source-apportionment studies. The SARS-CoV-2 lockdown period was a unique opportunity to test how any possible reductions in urban transport parameters may improve the air quality in the city. The results suggest that even traffic-free conditions could not cause substantial reductions in pollution levels since several primary emission sources dominate the pollution profile over the city.

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## CRediT authorship contribution statement

**Aiymgul Kerimray:**Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Visualization, Project administration.**Nassiba Baimatova:**Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Visualization, Project administration.**Olga P. Ibragimova:**Validation, Formal analysis, Investigation.**Bauyrzhan Bukenov:**Validation, Formal analysis, Investigation.**Bulat Kenessov:**Writing - review & editing, Supervision, Funding acquisition.**Pavel Plotitsyn:**Validation, Formal analysis, Investigation.**Ferhat Karaca:**Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Visualization, Supervision.

## Declaration of competing interest

No potential conflict of interest was reported by the authors. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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