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ORIGINAL ARTICLE

Seasonal Variations and Effect of COVID-19 Lockdown Restrictions on the Air Quality in the Cities of Kazakhstan

Nassiba Baimatova[1] · **Anara Omarova**[1] · **Aset Muratuly**[1] · **Madina Tursumbayeva**[1,2] · **Olga P. Ibragimova**[1] · **Bauyrzhan Bukenov**[1] · **Aiymgul Kerimray**[1]

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Abstract

The objective of this study was to investigate the impact of COVID-19 lockdown on different air pollutants in eight cities of Kazakhstan by employing the data from the National Air Quality Monitoring Network. We selected eight cities located in different regions of the country with varied climatic and geographic conditions and emissions sources, providing good conditions for studying the differences in responses of air quality to COVID-19. Due to severe winters, the heating season in Kazakhstan has a significant impact on air quality; therefore, annual winter/spring changes in air quality were also compared. The positive effect of the COVID-19 lockdown (spring 2020) on NO_2 and CO levels was observed in 5 and 3 cities, respectively (out of 8). Total Suspended Particles and SO_2 exhibited a more complicated response to COVID-19 lockdown: cities had a varying effect. No impact of lockdown measures was observed in industrial cities (Ust-Kamenegorsk and Karagandy), but seasonal changes were significant. In addition, despite some improvements during the lockdown period, the air quality in seven out of eight cities was still below the safety levels. The atmospheric quality in urban areas of Kazakhstan has not improved significantly due to the lockdown measures. This study underscores the importance of imposing stricter air quality emission control over industrial enterprises and coal-fired power plants.

Highlights

- Response of air quality to COVID-19 lockdown in eight cities of Kazakhstan was examined
- The positive effect of the COVID-19 lockdown on NO_2 and CO was observed in 5 and 3 cities, respectively

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✉ Nassiba Baimatova
baimatova@cfhma.kz

✉ Aiymgul Kerimray
aiymgul.kerimray@cfhma.kz

[1] Center of Physical-Chemical Methods of Research and Analysis, Faculty of Chemistry and Chemical Technology, Al-Farabi Kazakh National University, 96a Tole bi Street, 050012 Almaty, Kazakhstan

[2] Department of Meteorology and Hydrology, Al-Farabi Kazakh National University, Almaty, Kazakhstan

- The effect of the quarantine measures on SO_2 and TSP was different in different cities
- Industrial cities were not affected by the lockdown, but seasonal changes were significant
- NO_2 and SO_2 concentrations exceeded the WHO limits during the COVID-19 lockdown period

Keywords Air quality · Pollution · Monitoring · COVID-19 · Lockdown · Kazakhstan

1 Introduction

The Central Asian region has only recently become well-known for its severe air pollution, owing to developments in real-time air quality monitoring in the past few years. Even though the population density is relatively low compared to other regions of Asia, Central Asian countries (including Kazakhstan) hold the leading positions in the world's most polluted country ranking. Kazakhstan was ranked 23rd most polluted country in the world, with an annual average $PM_{2.5}$ (Particulate Matter) concentration of 23.6 $\mu g/m^3$ in 2019 (IQAir.com 2021). Despite the high IQAir ranking, the number of studies related to air quality in Kazakhstan according to the Web of Science Core Collection search is lower in comparison with such countries as the United States of America (USA), United Kingdom (UK), China, India, etc. (Table 1). In the wintertime, some cities of Kazakhstan (e.g., Nur-Sultan, Almaty, Karagandy) are frequently among the top ten polluted cities globally, with $PM_{2.5}$ concentration levels ranging between 100 – 200 $\mu g/m^3$ (IQAir.com 2021).

The first SARS-CoV-2 infection (COVID-19) case was registered in Kazakhstan on 13 March 2020. A nationwide emergency was declared in Kazakhstan three days later (on 16 March 2020). To control the spread of COVID-19 in Kazakhstan, the Government of Kazakhstan announced several restrictive measures, including closing of schools, universities, non-essential business, production, and shopping centers. The exceptions were made for life-supporting facilities and strategic enterprises. As of 25 July 2021, 542,703 cases and 5,538 deaths among the 18.9 million population were registered in Kazakhstan (Ministry of Healthcare of the Republic of Kazakhstan 2021). The application of severe and unprecedented restriction measures over several weeks led to the virtual absence of vehicle traffic, and the closure of small businesses, which significantly impacted people's

Table 1 Number of studies in keywords "Air Quality" and the name of the country on "world's most polluted countries" IQAir ranking (IQAir.com 2021)

Country	Number of Studies	IQAir ranking
China	10,776	22
USA	5128	90
India	2499	5
UK	1302	94
Germany	1026	89
Indonesia	399	17
Bangladesh	194	1
Kazakhstan	50	23

daily routines. Despite severe restriction measures, primary stationary sources of emissions continued to operate in Kazakhstan, including coal-fired power plants, metallurgical industries, and oil refinery plants. Restriction measures resulted in a substantial reduction of traffic movements in the cities of Kazakhstan in an unprecedented way, creating unique conditions to assess the impact of the traffic-free conditions on air pollution in the cities of Kazakhstan.

The global COVID-19 pandemic caused unprecedented impacts on the economies, environment, and behaviours forming a new agenda for research (Helm 2020). The reduction in air pollution due to the decline of economic activities during lockdown was reported by many authors across the world (Mousazadeh et al. 2021) (Supplementary Material (SM); Table SM1). The positive effect of COVID-19 lockdown on air quality improvement, mainly reduction of NO_2 and CO concentrations, was observed in some parts of India (Allu et al. 2021; Bera et al. 2021; Chelani and Gautam 2021; Gopikrishnan et al. 2022), Italy (Collivignarelli et al. 2020; Gautam 2020), China (Chen et al. 2020b; Gautam 2020), Spain (Gautam 2020; Tobías et al. 2020; Pey and Cerro 2022), France (Gautam 2020), Vietnam (Nguyen et al. 2022), Russia (Ginzburg et al. 2020), Canada (Tian et al. 2021), USA (Liu et al. 2021), Turkey (Şahin 2020) and Malaysia (Ash'aari et al. 2020). However, the impact of lockdown measures was not uniform across different pollutants and areas. Some studies found insignificant changes in SO_2 or PM_{10} concentrations (Pei et al. 2020; Kerimray et al. 2020b; Assanov et al. 2021a; von Schneidemesser et al. 2021; Bontempi et al. 2022), which can be explained by the contribution of the non-traffic emissions sources. Despite the decrease in primary pollutants concentrations, it was observed that secondary pollutants levels, such as O_3 increased (Li and Tartarini 2020; Sharma et al. 2020; Kerimray et al. 2020b; Bera et al. 2021; von Schneidemesser et al. 2021; Lou et al. 2022). Zangari et al. (2020) showed no changes in air quality in New York City (USA) during the COVID-19 pandemic and assumed that improvement in air quality could occur in places with high levels of air pollutants compared to locations with relatively clean air. Also COVID-19 restrictions did not lead to a substantial reduction in air pollution levels in Beijing, Wuhan, Guangzhou (China) (Pei et al. 2020) and Almaty (Kerimray et al. 2020b), Ust-Kamenogorsk (Assanov et al. 2021b) (Kazakhstan). Huang et al. (2021) found that despite significant decreases in the concentration of primary pollutants during COVID-19 lockdown, there were periods of heavy haze pollution in eastern China, which was caused by the enhancement of secondary pollution. In northern China, there was an unexpected $PM_{2.5}$ and ozone increase during the COVID-19 outbreak, which was explained by meteorological factors and uninterrupted emissions from power plants and petrochemical facilities (Le et al. 2020). Hashim et al. (2021) reported that PM_{10} and $PM_{2.5}$ concentrations during the lockdown in Baghdad (Iraq) exceeded the WHO daily limits, indicating that stationary pollution sources contributed to air quality deterioration. Kroll et al. (2020) stated that chemical transformations in the atmosphere contribute to the extent to which COVID-19-induced emission reductions impact air quality. Varying impacts of lockdown on air quality levels could be attributed to the different structure of emission sources, along with the unique local topography and meteorological conditions.

In Kazakhstan, the impact of COVID-19 restriction measures on air quality was studied in two cities: Almaty (Kerimray et al. 2020b; Ibragimova et al. 2021) and Ust-Kamenogorsk (Assanov et al. 2021b). Assanov et al. (2021b) reported that the concentration of Total Suspended Particles (TSP) increased by 13–21%, while SO_2 and NO_2 levels did not change significantly in Ust-Kamenogorsk (Kazakhstan) during the lockdown. In Almaty (Kazakhstan), concentrations of CO, NO_2, and $PM_{2.5}$ decreased by 49, 35 and 21%, respectively, with an insignificant increase of SO_2 (Kerimray et al. 2020b). The changes of volatile organic compound concentrations during the lockdown in Almaty showed an increase in the levels of benzene and toluene by 2–3 times (Kerimray et al. 2020b) and in the levels of ethylbenzene and benzaldehyde by 2–5 times (Ibragimova et al. 2021). Thus, air pollution could be substantially improved during the lockdown in the cities where transport was a major source. However, air quality improvement could be moderate in the areas with a more complex combination of sources, with a substantial contribution of other sources, which were not affected by restriction measures (e.g., heavy industry, power plants).

In Kazakhstan, air quality improvement in spring 2020 compared to winter 2020 could be attributed not only to the lockdown but also to the end of the heating season, because heating systems (burning coal or natural gas) are frequently among the largest sources of pollutant emissions in the cities. Heating is an essential survival need in Kazakhstan due to the severe winter, particularly in the north. In Kazakhstan's urban areas, district heating systems (using coal or natural gas) are widely used (Kerimray et al. 2017). The "heating season" starts when the average daily air temperature falls below 8 ℃ for three consecutive days. Buildings that are not connected to district heating, rely on small-scale household-level heating stoves and boilers that burn coal, wood, or natural gas, depending on pipeline gas availability (Kerimray et al. 2017). The heating season starts in September in the north and October–November in the south and lasts until April (except for Shymkent where it ends in early April) (Table SM2). This study aims to explore the response of air quality not only to the lockdown, but also to analyze seasonal variations. The impact of the heating season on air quality in the cities under consideration was assessed by comparing air pollutant concentrations in the winter with spring in 2018–2019. To quantify the impact of the heating season, the 2020 year was not considered because the aim is to analyze the seasonal variations without a lockdown effect.

In this study, the impact of COVID-19 lockdown on air quality was estimated in the eight cities of Kazakhstan using data from 28 ground-based monitoring stations. Selected eight cities are in different regions of the country (North, South, West, Center, and East), characterized by different climatic and geographic conditions because of varying geographic latitudes (from 42º 18' N to 49º 57' N). In addition, they are characterized by varying profiles of sources of emissions: urban populated cities (Almaty, Shymkent, and Nur-Sultan), cities with metallurgical industry, and/or heavy reliance on coal (Karaganda, Ust-Kamenogorsk, and Petropavlovsk), cities with oil industry (Aktau, and Atyrau). This research provides a unique possibility to study differences in responses to such factors as COVID-19 lockdown measures and heating season in selected eight cities located in different regions of Kazakhstan at a distance from each other. To the best of the authors' knowledge, there has not been yet any comprehensive assessment of the air quality changes during the lockdown in Kazakhstan using data from different cities.

Concentrations of TSP, NO_2, SO_2, and CO (obtained from the National Air Quality Monitoring Network (NAQMN)) during the state of emergency (56 days, 16 March – 11 May 2020) were compared with those during the same period (56 days) in the previous years (2018, 2019). Seasonal changes in air quality were also analyzed by comparing the air quality levels during the period of 20 January – to 15 March (winter) with 16 March – to 11 May (spring) for several years (2018–2020).

2 Methodology

2.1 Study Area

In this study, air quality in eight cities of Kazakhstan was evaluated: Aktau, Almaty, Atyrau, Karagandy, Nur-Sultan, Petropavlovsk, Shymkent, and Ust-Kamenogorsk (Fig. 1). These cities accommodate 5.7 million people, representing 30% of the total population and 53% of the urban population of Kazakhstan. Almaty, Nur-Sultan, and Shymkent are separate administrative-territorial units and the three the most populous cities of Kazakhstan. Five other cities (Aktau, Atyrau, Karagandy, Petropavlovsk, and Ust-Kamenogorsk) are administrative centers of their respective regions. Aktau and Atyrau are located in the west of Kazakhstan, with oil fields located less than 200 km away from those cities. Karagandy and Ust-Kamenogorsk are two industrial cities in Kazakhstan's Central and Eastern parts. Petropavlovsk is the most northern major city of Kazakhstan. Table SM2 summarizes information on the population at the beginning of 2020 (Bureau of National statistics 2020a) and major stationary sources of emissions among selected cities (Akimat of Mangystau region 2017; International green technologies and investment projects center 2019; Akimat of Shymkent city 2020; Darynova et al. 2020).

Kazakhstan ranks ninth in the world's largest countries, with a total area of more than 2.7 million km^2. All studied cities are in different administrative regions with considerably varying geographic latitudes and topography. Since Almaty is in a mountainous area, frequent temperature inversions and calm winds may affect the air quality in the city. Ust-Kamenogorsk is in a river valley surrounded by the Kalbinsky mountain ranges. Aktau and Atyrau are close to the Caspian Sea, creating conditions for the pressure difference and, as a result, constant strong winds. The lowland regions of Kazakhstan include Petropavlovsk, Nur-Sultan, Karaganda, and Shymkent. Each city has different climatic characteristics from the other due to geographical and topographical differences. Southern cities (Almaty, Aktau, Atyrau, and Shymkent) have higher average annual temperatures of about 10.4 – 13.3 °C, while northern has an average annual temperature of about 2.5 – 3.9 °C,

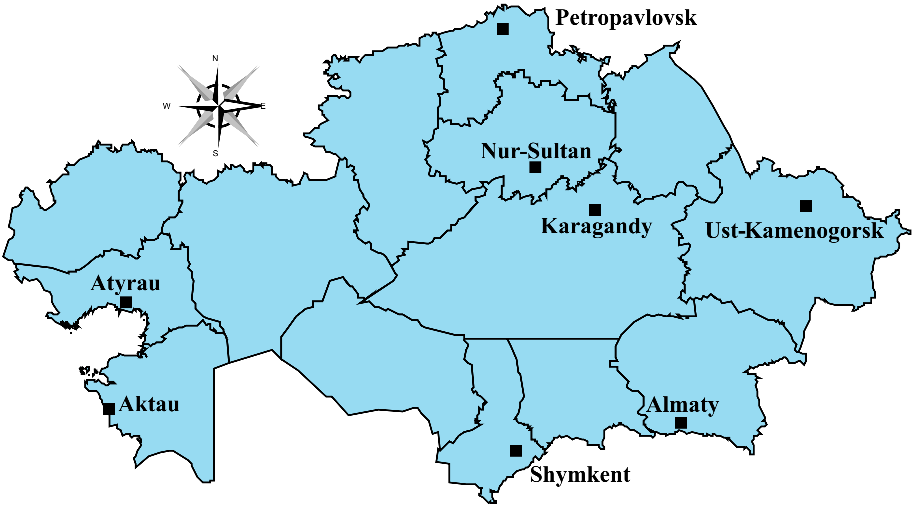

Fig. 1 Map showing the location of the studied cities

implying that northern cities will have extended heating season than southern ones (Pogodaiklimat.ru 2022).

2.2 Restriction Measures

The emergency due to the COVID-19 outbreak was nationally imposed on 16 March 2020 in Kazakhstan. The scheme of activities regulated during the state of emergency (from 16 March to 11 May 2020) by the selected cities is presented in Fig. SM1. After the state of emergency was announced, quarantines were imposed in the eight cities studied, with slightly different start and end dates (Fig. SM1) (Government decree 2020). The first lockdown was introduced in Almaty and Nur-Sultan on 19 March 2020 with the gradual removal of restrictive measures since April 27, 2020. The shortest lockdown period was in Karagandy (16 – 27 April 2020). The lockdown in Shymkent, Atyrau, Petropavlovsk, and Aktau was introduced on 27 March, 30 March, and 3 April 2020, respectively, with the consecutive opening of some enterprises from 26 – 27 April and 1 May 2020. The lockdown in Ust-Kamenogorsk was started on April 2 with subsequent mitigation of restrictive measures on April 29, 2020. Because of various lockdown periods, the period between March 16 and May 11, 2020 (end of the state of emergency) was considered a lockdown period in all eight cities.

The COVID-19 lockdown was characterized by strict measures, including the prohibition of leaving the places of residence, with exceptions for work and basic needs (grocery shopping and getting medical support). Movements by car or public transport within the city were allowed only with special permission. Air, railway, and inter-city travel were restricted, except for the state flights and movements of services that ensure public health. All educational institutions, such as schools, and universities were closed or transferred to online learning for the whole lockdown period. Places of entertainment and sports and small and medium-sized enterprises that do not produce vital products were closed. Power plants and Heating boiler stations continued their operation during lockdown because they were listed as "life-supporting facilities".

2.3 Data Collection and Pre-processing

TSP, NO_2, SO_2, and CO data for the eight selected cities were obtained for January 2018 to August 2020 from the National Hydrometeorological Service of Kazakhstan "Kazhydromet", which is the owner and operator of the NAQMN. Measurements from 28 monitoring stations were analyzed in this study: two stations in Aktau, five stations in Almaty, two stations in Atyrau, four stations in Karagandy, four stations in Nur-Sultan, two stations in Petropavlovsk, four stations in Shymkent, and five stations in Ust-Kamenogorsk (Table SM3). TSP, NO_2, SO_2, and CO were measured using the gas sampler (aspirator) OP-824TTs, gas analyzer K-100 and filters AFA-PV-20–1 for the aspirator OP-280 (all made in Russia). "Kazhydromet" publishes data on air pollutants in information bulletins on a monthly and annual basis. Manual air quality measurements are carried out 3–4 times a day. Descriptive statistics of the pollutant concentrations over the spring period by years are presented in Table 2 and data over winter by years is presented in Table SM4.

The wind speed, wind direction, temperature, relative humidity, and precipitation were obtained from the http://rp5.kz website (Table 3) (Rp5.kz Reliable Prognosis-5 2021), which collects data from the National Oceanic and Atmospheric Administration (USA).

Table 2 Descriptive statistics of the pollutant's concentrations during the spring period by years

Analyte	Year	City	Aktau	Almaty	Atyrau	Karagandy	Nur-Sultan	Petropavlovsk	Shymkent	Ust-Kamenogorsk
CO (mg/m^3)	2018–2019	N	516	1376	516	1027	1051	516	1032	2000
		Mean	0.32	1.29	1.59	1.92	0.83	1.35	2.89	1.35
		SD	0.11	0.73	1.03	1.17	0.76	0.73	0.85	0.88
		Min	0.040	0.10	0.43	0.40	0.020	1.0	1.0	1.0
		25%	0.20	1.0	1.0	1.2	0.33	1.0	2.0	1.0
		50%	0.30	1.0	1.0	1.6	0.60	1.0	3.0	1.0
		75%	0.40	1.3	2.0	2.1	1.0	1.8	3.0	1.0
		Max	0.70	5.0	12	8.9	6.7	6.0	9.0	10.0
	2020	N	258	672	258	571	543	257	515	857
		Mean	0.32	1.12	0.58	1.91	0.60	0.99	2.35	1.26
		SD	0.15	0.56	0.22	1.58	0.33	0.12	0.83	0.77
		Min	0.020	0.20	0.20	0.50	0.10	0.020	1.0	0.50
		25%	0.20	1.0	0.40	1.1	0.36	1.0	2.0	1.0
		50%	0.30	1.0	0.50	1.3	0.56	1.0	2.0	1.0
		75%	0.40	1.0	0.72	2.0	0.80	1.0	3.0	1.0
		Max	1.2	6.0	1.0	12	1.6	1.0	4.0	7.0

Table 2 (continued)

Analyte	Year	City	Aktau	Almaty	Atyrau	Karagandy	Nur-Sultan	Petropavlovsk	Shymkent	Ust-Kamenogorsk
NO_2 (µg/m^3)	2018–2019	N	516	1376	516	1027	1051	516	1032	2000
		Mean	18.3	100.1	66.3	51.0	98.3	32.3	79.8	61.7
		SD	5.0	66.6	15.4	23.5	138.6	22.5	15.4	36.4
		Min	7.00	5.00	10.0	10.0	10.0	3.00	11.0	20.0
		25%	15.0	50.0	60.0	30.0	10.0	20.0	70.0	40.0
		50%	18.0	90.0	70.0	50.0	30.0	30.0	80.0	50.0
		75%	22.0	130.0	80.0	70.0	110.0	40.0	90.0	80.0
		Max	37.0	450	120	150	670	220	130	310
	2020	N	258	672	258	571	543	257	515	857
		Mean	15.57	73.56	34.65	49.89	68.25	21.84	80.87	58.83
		SD	3.10	52.66	10.74	10.28	72.51	10.98	20.35	29.95
		Min	9.00	10.0	10.0	30.0	10.0	10.0	40.0	20.0
		25%	13.0	40.0	30.0	40.0	20.0	10.0	70.0	40.0
		50%	15.0	60.0	30.0	50.0	30.0	20.0	80.0	50.0
		75%	18.0	100	40.0	50.0	140	30.0	90.0	70.0
		Max	26.0	300	70.0	110	320	70.0	130	230

Table 2 (continued)

Analyte	Year	City	Aktau	Almaty	Atyrau	Karagandy	Nur-Sultan	Petropavlovsk	Shymkent	Ust-Kamenogorsk
TSP ($\mu g/m^3$)	2018–2019	N	516	1376	516	1027	1051	516	1032	2000
		Mean	126.4	139.8	267.2	182.1	571.8	106.8	270.7	161.7
		SD	76.9	77.8	257.4	115.5	479.4	37.5	60.3	112.1
		Min	10	60	100	100	100	100	20	100
		25%	60	100	100	100	200	100	200	100
		50%	120	100	200	100	400	100	300	100
		75%	180	200	300	200	800	100	300	200
		Max	330	600	2100	800	2300	400	400	1000
	2020	N	258	672	258	571	543	257	515	857
		Mean	42.1	159.5	280.3	132.3	197.3	100.0	223.7	127.4
		SD	36.3	78.5	221.3	63.5	87.8	0	61.6	60.7
		Min	8.0	60	100	100	100	100	100	100
		25%	20	100	100	100	100	100	200	100
		50%	30	110	200	100	200	100	200	100
		75%	50	200	400	100	300	100	300	100
		Max	230	600	1100	400	400	100	400	400

Table 2 (continued)

Analyte	Year	City	Aktau	Almaty	Atyrau	Karagandy	Nur-Sultan	Petropavlovsk	Shymkent	Ust-Kamenogorsk
SO_2 (μg/m^3)	2018–2019	N	516	1376	516	1027	1051	516	1032	2000
		Mean	19.0	10.6	13.8	35.7	2.6	5.9	9.5	72.6
		SD	4.13	8.00	2.05	10.7	6.6	5.9	4.8	29.9
		Min	11	2.0	9.0	11	1.0	1.0	0.7	27
		25%	16	5.0	12	28	1.0	2.0	7.0	54
		50%	19	8.0	14	36	1.0	4.0	9.0	68
		75%	22	14	15	43	2.0	8	11	83
		Max	35	55	33	71	99	50	110	603
	2020	N	258	672	258	571	543	257	515	857
		Mean	12.81	8.74	13.61	36.58	2.07	7.45	8.31	86.91
		SD	2.71	6.80	1.45	6.26	0.60	6.19	2.18	41.03
		Min	6.00	1.00	10.0	20.0	1.00	1.00	3.00	50.0
		25%	11.0	5.00	12.0	33.0	2.00	4.00	7.00	65.0
		50%	13.0	6.00	14.0	36.0	2.00	6.00	8.00	78.0
		75%	15.0	11.0	15.0	39.0	2.00	9.00	10.0	95.0
		Max	23.0	45.0	18.0	63.0	5.00	43.0	14.0	449

Table 3 Average meteorological parameters during winter and spring periods and the same periods in the previous years (2018–2019) among eight cities in Kazakhstan

City	Temperature (°C)						Humidity (%)					
	2018 – 2019		2020		Difference (°C)		2018 – 2019		2020		Difference (%)	
	winter	spring	winter	spring	winter	spring	winter	spring	winter	spring	winter	spring
Aktau	2.4	11.7	5.0	11.7	**2.6**	0.0	73.3	66.8	70.7	61.6	**-3.6**	**-7.8**
Almaty	-1.5	12.4	1.4	12.8	**2.9**	0.5	75.9	61.1	71.5	59.7	**-5.8**	-2.4
Atyrau	-3.8	11.2	2.2	11.8	**6.1**	0.6	73.7	53.3	67.3	46.3	**-8.7**	**-13.1**
Karagandy	-12.4	4.2	-7.1	7.7	**5.3**	**3.5**	72.9	66.4	71.6	56.0	-1.8	**-15.6**
Nur-Sultan	-13.3	4.5	-7.0	8.4	**6.3**	**3.9**	75.7	65.1	78.2	57.1	**3.3**	**-12.2**
Petropavlovsk	-15.1	2.8	-6.9	7.5	**8.2**	**4.7**	72.0	67.3	78.0	60.6	**8.3**	**-9.9**
Shymkent	3.5	14.4	4.1	14.8	0.6	0.5	71.7	64.4	75.9	61.5	**5.8**	**-4.6**
Ust-Kamenogorsk	-12.5	6.3	-6.3	8.5	**6.2**	**2.2**	76.6	66.7	70.8	56.7	**-7.5**	**-15.0**
City	Cumulative precipitation (mm)						Wind Speed (m/s)					
	2018 – 2019		2020		Difference (%)		2018 – 2019		2020		Difference (%)	
	winter	spring	winter	spring	winter	spring	winter	spring	winter	spring	winter	spring
Aktau	45	58	35	39	-22.5	-32.8	3.7	3.8	4.2	3.9	**13.6**	0.9
Almaty	165	403	198	373	20.1	-7.3	0.3	0.4	0.3	0.5	19.3	6.6
Atyrau	23	85	27	67	18.1	-21.3	3.6	3.7	3.8	3.9	4.5	6.0
Karagandy	76	145	156	56	**105.0**	**-61.3**	2.4	2.8	3.1	2.8	**27.0**	-1.8
Nur-Sultan	59	126	154	92	**162.2**	-27.5	1.9	2.2	2.6	1.9	**33.4**	**-15.4**
Petropavlovsk	23	51	47	47	100.9	-8.0	3.4	3.9	4.0	4.7	**19.5**	**20.0**
Shymkent	266	233	277	369	4.2	**58.3**	1.6	1.5	1.6	1.6	2.5	6.8
Ust-Kamenogorsk	134	182	178	53	33.5	**-70.7**	1.9	2.5	3.6	2.6	**88.0**	1.5

*Highlighted in bold – statistically significant ($p \leq 0.05$);

Difference in temperature is calculated by absolute change of temperatures

Locations of meteorological stations and descriptive statistics for the meteorology data are presented in Tables SM5 and SM6, respectively.

2.4 Method of Analysis

This study uses a comparative approach to analyze the impact of the COVID-19 lockdown on the atmospheric environment in the eight regionally representative cities. The period 20 January–15 March will be mentioned herein as 'winter', while the period 16 March–11 May will be mentioned as 'spring.' These terms were chosen to refer to the similar periods of pre-lockdown in previous years 2018 and 2019, and lockdown in 2020. The selection of the cities was based on their importance (administrative centers) and location in different regions of the country (North, South, West, Center, East). To distinguish trends in annual changes, the concentration of air pollutants during the 'winter' period was compared with the same period in the previous years (2018–2020). Additionally, meteorological parameters were assessed for the same periods, and their possible impacts on the air quality levels were discussed.

The mean of temperature, humidity, wind speed, pollutant concentrations, and the cumulative amount of precipitation during the winter and spring periods in 2018, 2019 and 2020 were calculated. The percent difference between them was calculated according to the Eqs. (1) and (2):

$$\%\ \mathrm{Difference\ between\ years} = \frac{\mathrm{C(2020)} - \mathrm{C(2019-2018)}}{\mathrm{C(2019-2018)}} \cdot 100 \tag{1}$$

$$\%\ \mathrm{Seasonal\ difference} = \frac{\mathrm{C(spring)} - \mathrm{C(winter)}}{\mathrm{C(winter)}} \cdot 100 \tag{2}$$

Statistical difference was tested using the paired samples *t*-test (two-tailed) at a 95% confidence level. Concentrations of pollutants were log-transformed to reduce the skewness and conform them to normality. Normality of data and outliers were identified using respective histograms and boxplots.

The correlation between meteorological parameters and log-transformed concentrations of pollutants was assessed using the Spearman correlation coefficients to find a core relationship between concentrations of pollutants as well as their relationship with temperature, relative humidity, and wind speed (Oduber et al. 2019) using daily average concentrations in winter and spring periods of 2018–2020. Spearman's rank correlation coefficient is a non-parametric degree of dependence of two variables described by a monotonic function. Coefficients of correlation have values between + 1 and -1, depending on the sign of the relationship.

3 Results and Discussion

3.1 Meteorological Data Analysis

Table 3 summarizes the meteorological data (air temperature, relative humidity, wind speed, and cumulative precipitation) for the selected cities for the winter and spring of 2020 and the same periods of 2018 and 2019. In comparison to other cities, the most northern cities in this study, Karagandy, Nur-Sultan, Petropavlovsk and Ust-Kamenogorsk, had the lowest average temperature values ranging from -12.4 ºC to -15.1 ºC in winter and from 2.8 ºC to 6.3 ºC in spring for 2018–2020 (Table 3). Other cities are in southern latitudes and, thus, are characterized by higher temperature values (Fig. 2). The average temperature varies from -3.8 ºC to 3.5 ºC during the winter and from 11.2 ºC to 14.4 ºC during the spring of 2018–2019. It should be noted that for all cities, except for Shymkent, the winter of 2020 was characterized by higher temperatures than the winter of 2018–2019. In addition, the northern cities (Karagandy, Nur-Sultan, Petropavlovsk, and Ust-Kamenogorsk) experienced significantly higher spring temperatures in 2020 than in 2018–2019.

The highest wind speed values for 2018–2019 were observed in Aktau, Atyrau and Petropavlovsk (from 3.4 to 3.9 m/s), and the lowest in Almaty (0.3 m/s). In other cities, the values for wind speed varied from 1.6 to 2.8 m/s. The values of cumulative precipitation tend to increase from winter to spring in all cities, except for Shymkent in 2018–2019 (Table 3).

The amplitude between winter and summer temperature values is considerable due to the severe continental climate. The natural transition from winter to spring causes significant temperature differences before and during the lockdown. The average temperature in the winter of 2020 was 5.0, 1.4, 2.2, -7.1, -7.0, -6.9, 4.1, -6.3 ºC, and in the spring of 2020 – 11.7, 12.8, 11.8, 7.7, 8.4, 7.5, 14.8, 8.5 ºC for Aktau, Almaty, Atyrau, Karagandy, Nur-Sultan, Petropavlovsk, Shymkent, and Ust-Kamenogorsk, respectively. In all considered cities, the relative humidity values were lower in spring than in winter 2020, with differences ranging from 9 to 21%. The relative humidity values in the spring of 2020 were lower than in the spring of 2018–2019. The spring period of 2020 was also characterized by lower precipitation values in Karagandy and Ust-Kamenogorsk, and higher precipitation values in Shymkent compared to the spring of 2018–2019. The values for wind speed in the spring of 2020 did not change significantly compared to the spring of 2018–2019, except for Nur-Sultan (decreased by 15.4%) and Petropavlovsk (increased by 20.0%).

3.2 Seasonal Variations of Air Pollutants

Table 4 presents the retrieved data on air quality parameters for the selected cities during the winter and spring of 2018–2020. The impact of the heating season on air quality in the cities under consideration was assessed by comparing air pollutant concentrations in the winter with spring in 2018–2019. Thus, the 2020 year was not considered in this subsection, because the aim was to analyze the seasonal variations without the lockdown effect.

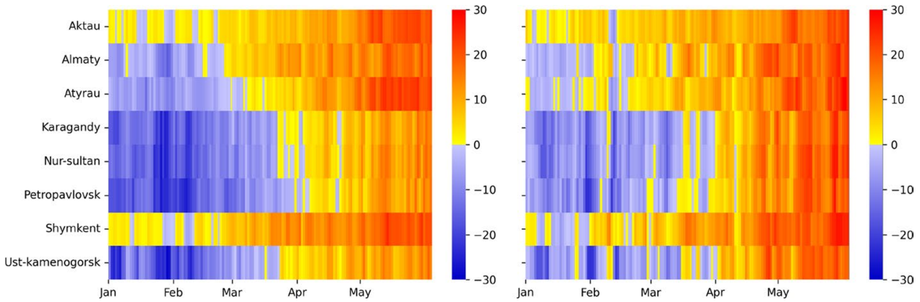

Fig. 2 Average daily temperature from 20 January to 11 May in eight cities: 2018 – 2019 (left), 2020 (right)

Table 4 Average air quality parameters during the winter and the spring

Analyte	Period	Winter			Spring			Difference (%)	
	Year	2018–2019	2020	Difference (%)	2018–2019	2020	Difference (%)	2018–2019	2020
CO[a]	Aktau	0.4	0.4	5.9	0.3	0.3	0.4	**-17.7**	**-22.0**
	Almaty	1.6	1.6	2.7	1.3	1.1	**-13.3**	**-20.6**	**-33.0**
	Atyrau	1.6	0.8	**-45.7**	1.7	0.6	**-64.9**	6.7	**-30.9**
	Karagandy	2.4	2.0	**-19.5**	1.9	1.8	-4.7	**-21.3**	-6.9
	Nur-Sultan	1.1	0.8	**-25.7**	0.9	0.6	**-29.6**	**-23.1**	**-27.1**
	Petropavlovsk	1.4	1.0	**-29.3**	1.3	1.0	**-26.5**	-3.6	0.3
	Shymkent	3.0	3.2	**4.5**	2.9	2.3	**-18.7**	**-4.7**	**-25.8**
	Ust-Kamenogorsk	1.6	1.4	**-12.0**	1.3	1.2	-7.4	**-17.7**	**-13.4**
NO_2[b]	Aktau	18.6	17.8	-4.7	18.3	15.6	**-14.9**	-1.9	**-12.3**
	Almaty	147.6	132.7	-10.1	101.9	73.4	**-28.0**	**-30.9**	**-44.7**
	Atyrau	69.1	44.6	**-35.4**	66.3	34.7	**-47.7**	**-4.1**	**-22.4**
	Karagandy	58.1	49.8	**-14.3**	51.0	50.1	-1.8	**-12.1**	0.6
	Nur-Sultan	96.0	106.2	10.7	94.6	57.4	-39.3	-1.5	-46.0
	Petropavlovsk	29.5	33.7	**14.1**	32.2	21.3	**-33.8**	9.2	**-36.6**
	Shymkent	73.6	94.1	**27.9**	79.8	80.9	1.3	**8.4**	**-14.1**
	Ust-Kamenogorsk	96.8	75.3	**-22.2**	60.9	57.8	-5.0	**-37.1**	**-23.3**
TSP[b]	Aktau	127.1	53.6	**-57.8**	126.4	42.1	**-66.7**	-0.6	**-21.5**
	Almaty	147.2	172.5	**17.2**	135.7	158.0	**16.5**	**-7.8**	**-8.4**
	Atyrau	194.0	203.3	4.8	250.5	251.2	0.3	**29.1**	**23.5**
	Karagandy	182.6	147.4	**-19.3**	171.5	126.7	**-26.1**	-6.1	-14.0
	Nur-Sultan	344.1	206.8	**-39.9**	688.9	194.7	**-71.7**	**100.2**	-5.8
	Petropavlovsk	116.5	100.0	**-14.2**	106.3	100.0	**-5.9**	**-8.8**	0
	Shymkent	273.6	290.1	**6.1**	270.7	223.6	**-17.4**	-1.1	**-22.9**
	Ust-Kamenogorsk	249.9	148.7	**-40.5**	144.3	119.7	**-17.0**	**-42.2**	**-19.5**

Table 4 (continued)

Analyte	Period	Winter			Spring			Difference (%)	
	Year	2018–2019	2020	Difference (%)	2018–2019	2020	Difference (%)	2018–2019	2020
SO_2[b]	Aktau	18.2	15.6	**-14.2**	19.0	12.8	**-32.7**	4.5	**-18.1**
	Almaty	12.2	14.2	**16.1**	10.4	8.6	**-17.0**	**-15.3**	**-39.5**
	Atyrau	13.3	14.1	**6.1**	13.8	13.6	-1.4	**3.6**	**-3.7**
	Karagandy	51.5	37.5	**-27.2**	35.8	36.6	2.3	**-30.4**	-2.2
	Nur-Sultan	1.7	3.8	**120.2**	2.6	2.1	-20.9	53.2	-45.0
	Petropavlovsk	4.8	5.8	**19.5**	5.9	7.4	**25.2**	**23.0**	**28.9**
	Shymkent	8.2	10.0	**22.9**	9.5	8.3	**-12.6**	**16.6**	**-17.1**
	Ust-Kamenogorsk	140.4	110.8	-21.1	72.6	86.2	**18.9**	**-48.3**	**-22.2**

*Highlighted in bold – statistically significant ($p \leq 0.05$);

Concentration units: a – mg/m^3, b – μg/m^3

During the study period, selected cities are characterized by varying NO_2, CO, TSP, and SO_2 concentrations (Table 4). The results depicted that in most of the selected cities, CO and NO_2 (in 6 and 4 cities out of 8, respectively) levels decreased in the spring compared to the winter, while the response to seasonal changes for SO_2 and TSP was more complicated, as concentration levels decreased in some cities and increased in others.

Concentrations of CO dropped by 5–23% on average in spring in six cities (Aktau, Almaty, Karagandy, Nur-Sultan, Shymkent, and Ust-Kamenogorsk) compared to the winter concentrations in 2018–2019 (Table 4). NO_2 levels declined in the spring (compared to winter) in four cities: Almaty (31%), Atyrau (4%), Karagandy (12%), and Ust-Kamenogorsk (37%). Reductions in NO_2 and CO can be explained by the seasonal decline of heat-production by coal-fired Combined Heat and Power plants (CHPs), which are one of the primary sources of NO_2, and by the longer time required for automobile catalytic converters to reach operating temperature in winter (Gaffney and Marley 2009), which increases CO and NO_2 emissions. The least significant reduction in NO_2 was observed in Atyrau, where gas-fired power plants are used (Table SM2). In contrast, there was a tendency for NO_2 concentrations to increase in Shymkent (8%), and this is most likely due to the rapid increase of total vehicle number in the city by 80% (26,719 vs 48,127 cars in December 2018 and May 2019, respectively) (Bureau of National Statistics 2020b).

In terms of SO_2, the decline in concentration levels was observed in three cities: Almaty, Karagandy, and Ust-Kamenogorsk (by 15, 30, and 48%, respectively). In contrast, SO_2 levels in Atyrau, Petropavlovsk, and Shymkent increased in the spring compared to the winter levels (4%, 23%, and 17%, respectively).

In the spring compared to the winter, the concentrations of TSP decreased by 8%, 9%, and 42% in Almaty, Petropavlovsk, and Ust-Kamenogorsk, respectively, whereas in Atyrau and Nur-Sultan, those levels increased by 29 and 100%, respectively. Previous studies attributed winter peaks in the TSP and $PM_{2.5}$ levels to higher coal consumption

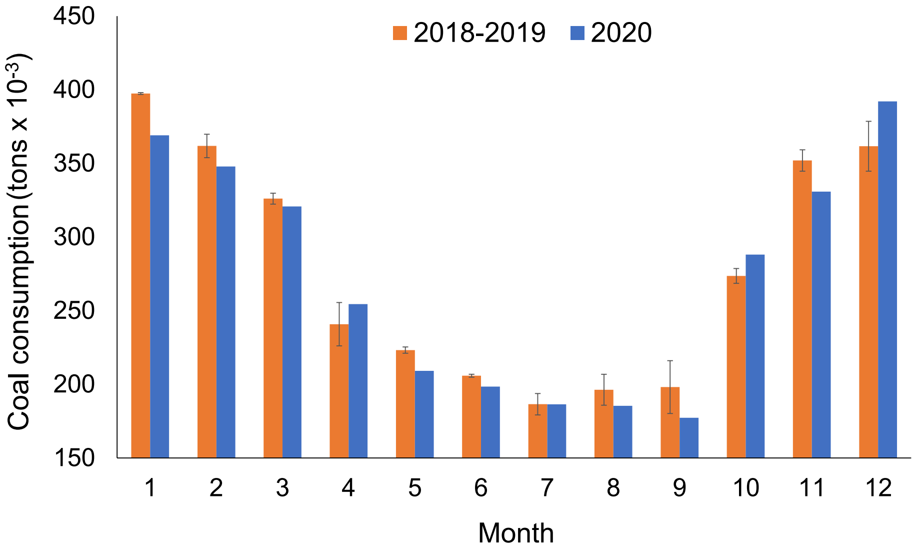

Fig. 3 Daily coal consumption in tones at the CHP-2 and CHP-3 in Almaty in 2018–2019 and 2020

during the heating season (Fig. 3) (Kerimray et al. 2020a; Assanov et al. 2021b) and poor dispersion conditions due to lower planetary boundary layer height (Ormanova et al. 2020; Tursumbayeva et al. 2022).

The days when NO_2 and SO_2 concentrations exceeded the WHO guideline limits for NO_2 (25 µg/m^3) and SO_2 (40 µg/m^3) show a general decreasing trend from winter to spring in the considered cities. In 2018, the number of days with NO_2 exceedance in spring was 7–80% lower compared to winter in studied cities, except Ust-Kamenogorsk and Petropavlovsk, where those increased by 79% and 16%, respectively. Most cities had low SO_2 levels, except for industrial cities Karaganda and Ust-Kamenogorsk, which had colder weather conditions and days with SO_2 levels exceeding the limit (Fig. 4). Karagandy had a sharper seasonal decrease of days exceeding SO_2 (64% in 2018 and 68% in 2019) than Ust-Kamenogorsk (6.5% in 2019).

3.3 The Effect of the Lockdown on the Concentration of Air Pollutants

Reduction of NO_2, CO, TSP, and SO_2 concentrations was observed during the lockdown in 2020, compared to respective periods in 2018–2019 for most cities. Compared to the same period in 2018–2019, NO_2 concentrations have significantly decreased in four cities (Table 4). The highest decrease of NO_2 concentrations was detected in Atyrau (-48%), while it was 15%, 28%, and 34% in Aktau, Almaty, and Petropavlovsk, respectively. Similarly, there was a reduction observed for Almaty during lockdown by 35% (Kerimray et al.

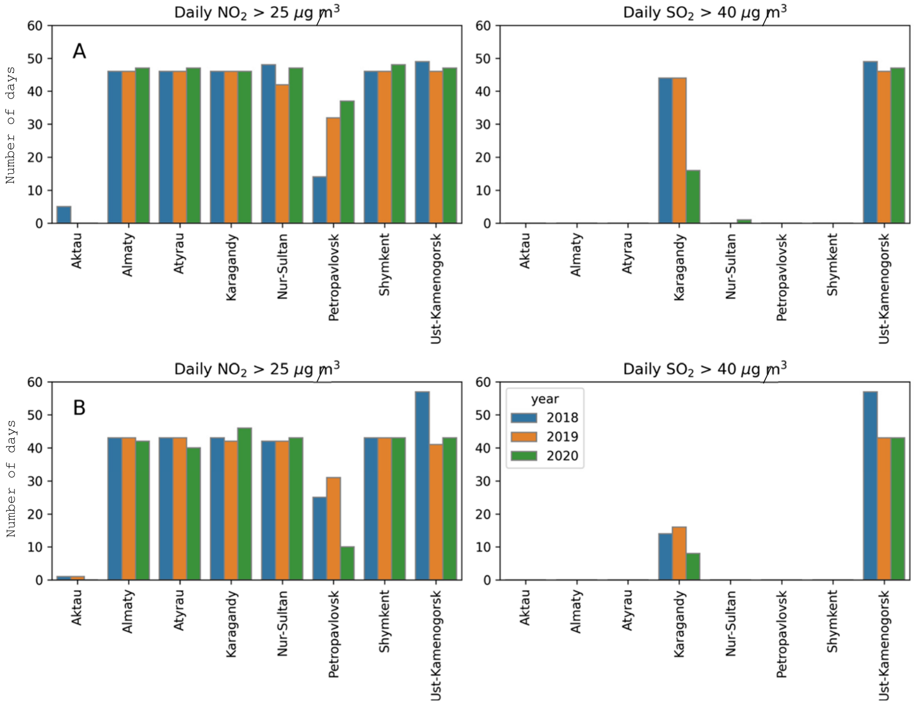

Fig. 4 Number of days exceeding WHO daily limit values during winter (**A**) and spring (**B**)

2020b). This drop can be attributed to the limitations imposed on transport usage in the cities, where in all cities, except Atyrau, only life-supporting facilities and delivery of essential goods were allowed to operate during the lockdown. Similar reductions have been reported in many other cities around the world, such as Wuhan (57%) (Pei et al. 2020), Berlin (40%) (von Schneidemesser et al. 2021), Madrid (50%) (Baldasano 2020), Barcelona (62%) (Baldasano 2020), New York (40%) (Chen et al. 2020a) and others. In other studied cities, the change in NO_2 concentrations during the lockdown period was insignificant compared to the same period in 2018–2019.

In some cities annual air quality changes occurred, which were estimated by comparing winter 2020 with the same period in the previous years. The reduction in NO_2 pollution in Atyrau during the lockdown can be only partially related to restrictions since the city experienced a general decline in NO_2 in winter 2020 compared to winter 2018–2019 (-35%). The NO_2 concentrations in Shymkent did not change considerably during the lockdown period compared to the same period in 2018–2019. However, considering that the NO_2 concentrations have an increasing annual trend in winter, the concentrations of NO_2 show a sharp decrease during the lockdown measures (Table 4).

Despite the reduction in NO_2 levels caused by the lockdown period, the number of days with NO_2 concentrations exceeding the WHO limits stayed nearly the same in all studied cities except Petropavlovsk. In this study, the results for NO_2 in Ust-Kamenogorsk are comparable with those of Assanov et al. (Assanov et al. 2021a). However, there is a difference in obtained results on CO, SO_2, and TSP in this study compared to the study by Assanov et al. (2021a), which are likely due to the differences in the definition of treatment (or studied) periods (emergency period vs. lockdown), years (2018–2020 vs. 2016–2020) and methodology.

The substantial decline of CO concentrations during the lockdown period was also observed in five considered cities. The reductions in the level of CO in Almaty, Shymkent, Atyrau, Petropavlovsk, and Nur-Sultan varied from 13 to 65%. Nur-Sultan and Petropavlovsk did not conclusively demonstrate that the lockdown measures solely caused the observed decrease because winter 2020 was characterized by a similar decrease in CO. Even though air quality in Atyrau has also improved annually in 2020, an unusual seasonal drop in CO in 2020 (-31%) was observed, which may indicate that quarantine measures contributed to this improvement in spring. Data from additional monitoring stations allowed the earlier studies (Kerimray et al. 2020b) to identify the declining trend in CO detected in Almaty. CO levels fell in numerous other cities worldwide with COVID-19 limitations (Collivignarelli et al. 2020; Allu et al. 2021; Bera et al. 2021; Tian et al. 2021).

SO_2 levels decreased significantly in three cities (Aktau, Almaty, and Shymkent), while in Ust-Kamenogorsk and Petropavlovsk, SO_2 climbed by 19% and 25%, respectively, during the lockdown period compared to the same periods in 2018–2019. General air quality trends may be partially responsible for reduced SO_2 in Aktau and increased SO_2 in Petropavlovsk during the lockdown period. In Nur-Sultan, Atyrau, and Karagandy, changes in SO_2 level were negligible during the lockdown compared with spring in 2018–2019. The lockdown measures did not impact the operation of industries and power and heating plants, and this can explain the slight changes or increases in SO_2 concentrations during the lockdown. Similar findings with varying trends of SO_2 concentration in different cities within the country were described in other studies (Filonchyk et al. 2021).

The concentrations of TSP declined significantly by 6–72% in Nur-Sultan, Petropavlovsk, Aktau, Karagandy, Shymkent, and Ust-Kamenogorsk during the lockdown period in comparison with spring in 2018–2019. For all cities, except Shymkent, the effect of restrictions was unclear due to a comparable 14–58% reduction in TSP in winter in 2020. Only in Aktau and in Nur-Sultan atypical seasonal TSP trends in 2020 could imply that restriction contributed to TSP decline. On the contrary, the concentrations of TSP increased in Almaty during the lockdown, and a similar increase was observed in winter.

Ust-Kamenogorsk and Karagandy are cities located in the north (with severely cold winters) and they are industrial centers where coal-burning and industry are strongly affecting air quality. Only these two cities (out of 8 cities) experienced days that exceeded SO_2 limit values established by WHO in the winter period (16–49 of 57 days) and in the spring period (8–57 of 57 days) each year in 2018–2020. Improvements in air quality during the lockdown were not noticed in Ust-Kamenogorsk and Karagandy, where most industrial facilities and coal-based CHPs continued to run normally. The only exception to this was TSP levels. At the same time, a decline in TSP levels in both cities did not indicate the lockdown effect, as reductions in TSP levels were observed in winter 2020 compared to the same period in 2018–2019. For China, SO_2 decreased in 309 out of 366 cities during the lockdown due to reduced emissions from secondary industries, which activities were prohibited during the pandemic (Wang et al. 2020). SO_2 levels in Ust-Kamenogorsk dramatically increased by 19% during the lockdown compared to spring 2018–2020, possibly to the rise of coal burning by households.

3.4 Spearman's Correlation Analysis

Table 5 presents the correlation coefficients between air pollutants (NO_2, CO, TSP, and SO_2) and meteorological parameters in the cities of Kazakhstan during the winter and spring periods of 2018–2020.

Concentrations of air pollutants showed weak to strong correlation with each other, as well as with meteorological parameters (ρ varied from 0.01 to 0.76) (Table 5). Wind speed can substantially impact air quality (Li et al. 2019). Wind speed had a significant negative correlation (two-tailed, $p < 0.0005$) with concentrations of CO (in 4 out of 8 studied cities), with NO_2 (in 2 out of 8 cities), with SO_2 (in Karagandy and Ust-Kamenogorsk). TSP concentrations negatively correlated with wind speed in Karagandy and Ust-Kamenogorsk, improving the air quality due to horizontal dispersion. However, Atyrau wind speed had a strong positive correlation with TSP ($\rho = 0.70$), indicating possible contribution of wind-carried suspended particles. A similar positive but insignificant correlation was observed for Aktau. It is noteworthy that both cities are located near the Caspian Sea, which could be a common source of particles (Prijith et al. 2014). Horizontal dispersion with wind speed was also observed for NO_2 in Almaty and Ust-Kamenogorsk; both cities have low average wind speed with frequent calm weather (Table 3).

Temperature is one of the main factors influencing atmospheric air pollution (Barzeghar et al. 2022). A strong negative correlation with temperature was observed for CO concentrations in all studied cities, especially for Almaty, Karagandy, Ust-Kamenogorsk, and Nur-Sultan, indicating improved air quality during warmer periods. TSP concentrations significantly negatively correlated with temperature in Karagandy, Ust-Kamenogorsk, and Petropavlovsk ($\rho = -0.27$, -0.61, and -0.20, respectively), most probably due to the end of the heating season and thus lesser amount of coal use. SO_2 concentrations had similar correlations with temperature with significant and strong negative correlation in Karagandy, Ust-Kamenogorsk, as well as in Almaty. All three cities are heated with coal during winter, therefore, warmer periods have improved air quality due to lesser fossil fuel use. 4 out of 8 studied cities had an insignificant correlation of NO_2 with temperature, except for Almaty, Atyrau, Karagandy, and Ust-Kamenogorsk due to similar reasons.

Table 5 Spearman correlation between the concentration of pollutants and meteorological parameters in 2018 – 2020

City	Parameter	TSP	SO_2	CO	NO_2
Aktau	TSP	1.0*	0.56*	0.02	0.28*
	SO_2	0.56*	1.0*	0.15	0.57*
	CO	0.02	0.15	1.0*	0.28*
	NO_2	0.28*	0.57*	0.28*	1.0*
	Temperature	0.01	-0.01	-0.22*	-0.05
	Humidity	-0.26*	-0.02	0.19*	-0.02
	Wind speed	0.09	-0.07	-0.26*	-0.15
Almaty	TSP	1.0*	0.25*	0.44*	0.26*
	SO_2	0.25*	1.0*	0.29*	0.33*
	CO	0.44*	0.29*	1.0*	0.59*
	NO_2	0.26*	0.33*	0.59*	1.0*
	Temperature	0.14	-0.15*	-0.28*	-0.37*
	Humidity	-0.49*	0.02	-0.07	0.04
	Wind speed	-0.03	-0.1	-0.25*	-0.23*
Atyrau	TSP	1.0*	0.07	0.03	-0.01
	SO_2	0.07	1.0*	0.0	-0.09
	CO	0.03	0.0	1.0*	0.76*
	NO_2	-0.01	-0.09	0.76*	1.0*
	Temperature	0.17	0.13	-0.25*	-0.29*
	Humidity	-0.26*	-0.05	0.2	0.23
	Wind speed	0.7*	-0.03	-0.02	-0.11
Karagandy	TSP	1.0*	0.28*	0.45*	0.34*
	SO_2	0.28*	1.0*	0.48*	0.39*
	CO	0.45*	0.48*	1.0*	0.43*
	NO_2	0.34*	0.39*	0.43*	1.0*
	Temperature	-0.27*	-0.63*	-0.41*	-0.32*
	Humidity	-0.1	0.28*	0.05	0.16
	Wind speed	-0.25*	-0.31*	-0.46*	-0.19
Nur-Sultan	TSP	1.0*	-0.02	0.13	0.04
	SO_2	-0.02	1.0*	-0.07	0.06
	CO	0.13	-0.07	1.0*	0.16*
	NO_2	0.04	0.06	0.16*	1.0*
	Temperature	0.07	0.0	-0.43*	-0.02
	Humidity	-0.07	0.06	0.09	0.06
	Wind speed	-0.02	0.12	-0.17	-0.03
Petropavlovsk	TSP	1.0*	0.11	0.18*	0.07
	SO_2	0.11	1.0*	-0.15	0.13
	CO	0.18*	-0.15	1.0*	0.06
	NO_2	0.07	0.13	0.06	1.0*
	Temperature	-0.2*	0.2*	-0.2*	0.11
	Humidity	0.04	-0.06	0.04	0.19*
	Wind speed	-0.18	0.13	-0.21*	-0.15

Table 5 (continued)

City	Parameter	TSP	SO_2	CO	NO_2
Shymkent	TSP	1.0*	0.29*	0.68*	0.25
	SO_2	0.29*	1.0*	0.39*	0.56*
	CO	0.68*	0.39*	1.0*	0.42*
	NO_2	0.25	0.56*	0.42*	1.0*
	Temperature	-0.24	0.02	-0.22*	0.02
	Humidity	0.01	0.11	0.01	0.08
	Wind speed	0.1	0.02	0.09	0.02
Ust-Kamenogorsk	TSP	1.0*	0.63*	0.6*	0.64*
	SO_2	0.63*	1.0*	0.43*	0.65*
	CO	0.6*	0.43*	1.0*	0.42*
	NO_2	0.64*	0.65*	0.42*	1.0*
	Temperature	-0.61*	-0.52*	-0.39*	-0.48*
	Humidity	0.34*	0.25*	0.19	0.33*
	Wind speed	-0.36*	-0.31*	-0.11	-0.31*

* – statistically significant ($p \leq 0.0005$)

Relative humidity (RH) had no significant correlation with concentrations of NO_2 and CO in the majority of the cities. A few significant positive correlations are partially due to the common correlation of concentrations of these pollutants and RH with temperature since winters are generally characterized by high relative humidity (Table 3). There was a significant negative correlation of TSP in Aktau, Almaty, and Atyrau with RH (higher than their correlation with temperature). This may be due to the settling effect of RH since it hinders the movement of coarse particles in the air. On the other hand, in Ust-Kamenogorsk, a significant positive correlation of TSP with RH was observed, which is probably due to a stronger correlation of TSP with temperature. Significant correlation with RH for SO_2 was observed only for Karagandy and Ust-Kamenogorsk mostly due to their common correlation with temperature.

SO_2 concentrations correlated (two-tailed, $p < 0.0005$) with TSP in 5 out of 8 selected cities. Although most of them had a significant positive correlation, it was exceptionally strong in Ust-Kamenogorsk and Aktau ($\rho = 0.63$ and 0.53), suggesting their common source in these cities. A moderately strong positive correlation between NO_2 and SO_2 was observed for most cities (ρ from 0.33 to 0.65), except for Atyrau, Nur-Sultan, and Petropavlovsk.

In general, Petropavlovsk is characterized by a low correlation of air pollutants concentration with meteorological parameters and between each other, and often with drastically different trends, compared to other cities with similar emission sources. This indicates this city's highly complex nature of air pollution, which requires further detailed analysis.

TSP concentrations correlated with CO moderately strongly in most of the studied cities, except for Aktau, Atyrau, and Nur-Sultan. This may suggest that fossil fuel use is the major contributing source to the concentration of suspended particulates in Almaty, Karagandy, Petropavlovsk, Shymkent, and Ust-Kamenogorsk. Moderate positive correlations of TSP with NO_2 were observed for Karagandy, and Ust-Kamenogorsk, Almaty, and Aktau.

NO_2 concentrations significantly correlated with CO concentrations in 7 out of 8 studied cities, except for Petropavlovsk. A strong correlation was observed for Atyrau, Almaty, Karagandy, Shymkent, and Ust-Kamenogorsk (ρ from 0.42 to 0.76), probably because they are emitted from a single major source.

4 Conclusions

The effect of the heating season, meteorological parameters, and COVID-19 lockdown on air quality in eight cities in Kazakhstan were investigated using the National Air Quality Monitoring Network data. The studied eight cities are spread across Kazakhstan, with varying topography, meteorological conditions, and emissions sources with varying meteorological, topographical, and emission sources. The selected cities have different air emission profiles: Almaty, Shymkent, and Nur-Sultan are urban populous cities; Karaganda, Ust-Kamenogorsk, and Petropavlovsk are cities with metallurgical industry and/or high reliance on coal; Aktau and Atyrau are cities with the oil industry.

There were varying responses to the COVID-19 lockdown by city and by pollutant. NO_2 and CO concentrations exhibited a decline in 5 and 3 cities out of 8 studied, respectively. During the lockdown, the mean NO_2 concentrations decreased from 14 to 48% in Aktau, Almaty, Atyrau, Shymkent, and Petropavlovsk, while CO average concentrations in Almaty, Atyrau, Nur-Sultan, Petropavlovsk, and Shymkent fell by 13–65%. However, in some cases, there were annual trends for improvement/worsening of air quality levels. As an example, the decrease in CO concentration in Petropavlovsk and Nur-Sultan was associated with an annual trend, which showed a decrease in CO levels in winter and spring 2020. SO_2 concentration responses to the lockdown are quite geographically dependent. The SO_2 concentrations decreased in Aktau, Almaty, and Shymkent, increased in Ust-Kamenogorsk and Petropavlovsk, and kept unchanged in Atyrau, Karagandy, and Nur-Sultan. In contrast, the COVID-19 lockdown exerted a significant influence on TSP concentrations and resulted in a decline from 17 to 72% in 3 out of 8 cities.

Analysis of the seasonal variations (winter/spring) in 2018–2019 demonstrated that the response was also different by pollutant type and city. Significant differences were found in the response of TSP, NO_2, CO, and SO_2 to the heating season. The findings showed that CO and NO_2 levels reduced in the spring compared to the winter in most of the examined cities (6 and 4 cities out of 8, respectively). The response to seasonal fluctuations for SO_2 and TSP was more convoluted as concentration levels declined in some cities while increasing in others.

In two industrial cities located in cold regions (Ust-Kamenogorsk and Karagandy), the air quality did not improve during the lockdown, possibly because most industrial facilities and coal-based Combined Heat and Power plants (CHPs) continued to run normally during COVID-19 lockdown. While in these two industrial cities seasonal variations were most pronounced compared to other cities. Consequently, the response to COVID-19 lockdown was not uniform by pollutant and city. Air quality levels exceeded WHO limit values during the lockdown. Therefore, understanding the contribution of sources in the considered cities is still vague.

This research has raised the significant air pollution issues in big cities of Kazakhstan, which requires a vast amount of further investigation, mainly concentrating on source apportionment. The complex relation between emissions, meteorology, diurnal, and seasonal variations, and chemical transformations in the atmosphere in the cities of Kazakhstan needs to be explored in future research studies.

The strengths of this study include: i) a relatively large number of observations for air pollutants concentrations with good spatial and temporal granularity; ii) selection of eight cities with different climatic and geographic conditions, and varying profiles of sources of emissions (urban, industrial); and iii) study effect of traffic-free conditions on air quality improvement. The limitations of this study are linked to air quality monitoring: i) manual sampling methods; ii) Total Suspended Particles were analyzed instead of $PM_{2.5}$ (for which monitoring data is not yet sufficient and/or available); and iii) lack of data on the concentration of the major air pollutants such as ozone and volatile organic compounds.

The obtained results of the study could be used to develop action plans for improving air quality. Decision-makers should focus on improving the continuous and reliable air monitoring system, increasing the number of stations, and the number of monitored pollutants, especially by separate monitoring of TSP fractions: PM_{10} and $PM_{2.5}$. Moreover, action plans for air quality improvement should include strict techniques for reducing, eliminating, or preventing air emissions. The low-grade with a high ash content coal used by households and CHPs for obtaining electricity and heating should be gradually banned, replaced with better quality, or with alternative fuel types (natural gas). CHPs and vehicles should use advanced emission control technologies. Strict standards for transport, industries, and power plant emissions are urgently required. This study provides the different contexts of air quality changes, which is extremely important for a large country like Kazakhstan. Since other countries in Central Asia also suffer from air quality challenges and often share similar conditions, this study can also have comprehensive applications to other countries.

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Author's Contributions NB and AK contributed to the study conception and design. Data collection and analysis were performed by AO, AM and MT. OI and BB wrote the first draft of the manuscript and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data Availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing Interest No potential conflict of interest is 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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