The impact of lockdown on nitrogen dioxide (NO₂) over Central Asian countries during the COVID-19 pandemic

Zhongrong Zhang¹ · Yijia Liu¹ · Haizhong Liu¹ · Aihong Hao² · Zhongwei Zhang¹

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Abstract

Nitrogen dioxide (NO₂) is one of the main air pollutants, formed due to both natural and anthropogenic processes, which has a significant negative impact on human health. The COVID-19 pandemic has prompted countries to take various measures, including social distancing or stay-at-home orders. This study analyzes the impact of COVID-19 lockdown measures on nitrogen dioxide (NO₂) changes in Central Asian countries. Data from Tropospheric Monitoring Instrument (TROPOMI) on the Sentinel-5 Precursor satellite, as well as meteorological data, make it possible to assess changes in NO₂ concentration in countries and major cities in the region. In particular, the obtained satellite data show a decreased tropospheric column of NO₂. Its decrease during the lockdown (March 19–April 14) ranged from −5.1% (Tajikistan) to −11.6% (Turkmenistan). Based on the obtained results, it can be concluded that limitations in anthropogenic activities have led to improvements in air quality. The possible influence of meteorology is not assessed in this study, and the implied uncertainties cannot be quantified. In this way, the level of air pollution is expected to decrease as long as partial or complete lockdown continues.

Keywords COVID-19 · Lockdown · Central Asian · TROPOMI · Nitrogen dioxide

Introduction

Nitrogen oxides (NO_x = NO₂ + NO) are among the main factors deteriorating the air quality due to their role as catalysts for the formation of ozone (O₃) and a number of secondary air pollutants that have a significant effect on human health, climate change, and environment (Atkinson et al. 2018). They are trace gases in the Earth's atmosphere. NO_x is a widespread anthropogenic emission. Sources of nitrogen oxides are combustion products of thermal power plants, exhausts from motor vehicles, and waste from metallurgical industries. As a result of photochemical reactions, oxides in the atmosphere become dioxides (Wünning and Wünning 1997).

Chinese authorities officially identified a new form of coronavirus in early January 2020. The World Health Organization (WHO) classified the coronavirus outbreak as COVID-19 on 11 February and designated the outbreak as a pandemic on the 11th March. As of 16 March 2021, there were already over 119.9 million confirmed cases of COVID-19 registered worldwide, and more than 2.6 million of them were fatal.

Central Asia is a forgotten region in terms of air quality research with an area of about 1.5 million km² and a population of over 72 million people. Although some studies have been carried out, they are not numerous and do not provide sufficient information to have a complete picture of the air quality in the region. Chen et al. (2013) conducted research on the relationship between particulate matter (PM) and aerosol optical depth (AOD) over Northern Tien-Shan. Liu et al. (2019) and Zhang et al. (2020) studied the sources and routes of aerosol transport over Central Asia. A study was also conducted to study the spatial-temporal characteristics of the AOD over Central Asia (Liu et al. 2020a, b; Wang et al. 2020a, b). According to previous studies, dust aerosols from sandstorms have the greatest impact on air quality (Indoitiu et al. 2012; Shi et al. 2020). However, air quality studies have not been carried out during the pandemic.

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✉ Zhongrong Zhang
gslzzr@sohu.com

¹ School of Mathematics and Physics, Lanzhou Jiaotong University, Lanzhou 730070, China

² School of Environmental and Municipal Engineering, Lanzhou Jiaotong University, Lanzhou 730070, China

The first cases of COVID-19 were reported in Central Asia in mid-March. Countries in the region were not prepared for the pandemic and responded in different ways. Kazakhstan, Kyrgyzstan, and Uzbekistan (Fig. 1) readily acknowledged the pandemic and declared a health emergency (Balakrishnan 2020; Kerimray et al. 2020). Various combinations of measures were implemented between March and May, including the introduction of strict regional or national quarantine measures (Ibbotson 2020). The lockdown measures have reduced mobility and social contacts, which has noticeably slowed the spread of the virus. Borders were closed, cities were quarantined, and public gatherings were banned. In contrast, Tajikistan and Turkmenistan initially did not recognize the presence of COVID-19 cases within country borders. Tajikistan has started reporting cases only after WHO officials visited the country in May, but did not take any strict measures to contain the spread of the virus. Turkmenistan denied having any cases of COVID-19 completely, although it may have accepted some of the WHO's recommendations, related to wearing masks and limiting entry to the country.

The lockdown measures have not only helped to slow down the spread of the virus, but also had a number of positive effects on air quality associated with a decrease in particulate matter ($PM_{2.5}$, PM_{10}), carbon monoxide (CO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) in different regions of the world (Ding et al. 2020; Liu et al. 2020a, b; Menut et al. 2020; Naeger and Murphy 2020; Filonchyk et al. 2020, 2021; Dursun et al. 2021; Jephcote et al. 2021). However, although major air pollutants were reduced;

nevertheless, in many places, O_3 increased during the lockdown periods. This is due to a decrease in NO_x , NO_2 , and CO concentrations. The reduction in NO_x emissions and concentrations has led to a reduction in O_3 depletion through the NO titration cycle (Sicard et al. 2020; Wang et al. 2020a, b; Grange et al. 2021). Nevertheless, the COVID-19 pandemic has negatively affected the global economy due to a sharp decline in economic growth in many countries, caused by suspension of many types of activities (Debone et al. 2020; Ming et al. 2020). Thus, the industrial sector, including the fuel and energy industry and petrochemical enterprises, worked with reduction in production volumes, while others were forced to cease their activities. Still, road transport, which is the main source of air pollution in urban areas, has decreased substantially (Sasidharan et al. 2020).

Anthropogenic activities are the main source of air pollution due to the emission of many harmful pollutants in large quantities that are harmful to human health. Nitrogen dioxide (NO_2) belongs to one of the most common types of air emissions of anthropogenic origin. NO_2 is formed by oxidation of NO, in turn formed in combustion processes. Their sources are various combustion products and waste from industrial enterprises. Its lifespan in the atmosphere is from 2 to 24 h (Goldberg et al. 2020; Shah et al. 2020). Due to their short lifespan, tropospheric NO_2 concentrations are highly dependent on local sources of NO_x emissions. Now, due to the COVID-19 pandemic, there is a widespread interest in rapidly assessing changes in NO_x emissions at short notice in areas where restrictive measures took place (Pacheco et al. 2020; Menut et al. 2020; Filonchyk and

Fig. 1 Location of Central Asian countries

Peterson 2020). The use of satellite data can be beneficial due to its global coverage and temporal resolution.

Thus, the purpose of this study is to assess changes in tropospheric NO₂ concentration in five countries in the central Asian region due to the lockdown measures taken during the COVID-19 pandemic. To achieve this goal, TROPOMI NO₂ tropospheric column was used.

Methods

Sentinel-5 Precursor (Sentinel-5P) is a space satellite launched on October 13, 2017 by the European Space Agency (ESA) for the purpose of daily global observation of the chemical composition of the Earth's atmosphere as well as the content and distribution of main pollutant gases, such as NO₂, SO₂, CO, CH₄, and O₃. The main payload of the satellite is the TROPOMI (Tropospheric Monitoring Instrument) sensor, which collects data in the ultraviolet (UV), visible (VIS), near (NIR), and mid-infrared (SWIR) ranges (Veefkind et al. 2012). Since August 6, 2019, the spatial resolution of the NO₂ product is 3.5 × 5.5 km at nadir with a wide swath of about 2600 km. The quality of individual TROPOMI observations depends on many factors, including cloud cover, surface albedo, existence of snow or ice, etc. These factors are taken into account when determining the quality assurance value (qa_value) available for each individual observation. This study uses data for which qa_value > 0.75 (Van Geffen et al. 2020). This is the recommended pixel filter, which excludes scenes with cloud radiance fraction > 0.5, scenes partially covered with snow and ice, as well as errors and problematic retrievals (Eskes and Eichmann 2020). NO₂ data were downloaded from the Copernicus Open Access Hub platform.

Average NO₂ concentrations over Central Asian countries were compared and analyzed between the lockdown period from March 19 to April 14, 2020 and the same period in 2019. In addition, NO₂ concentrations were compared between the periods before the lockdown (February 21–March 18), during the lockdown (March 19–April 14), and after the lockdown (April 15–May 11) 2020 and 2019. Tropospheric NO₂ data from the TROPOMI were processed to obtain the average column concentrations ($\pm$ standard deviation (SD)) over the specified periods, with units in $\mu\text{mol}/\text{m}^2$. Changes in NO₂ in each country were defined as the difference between the percentage of NO₂ concentration in 2019 and 2020.

To investigate the potential role of natural variability of different weather conditions in pollutant concentrations, meteorological data were used without using a chemical transport model. NO₂ data were analyzed with temperature, wind speed, and precipitation data. A significant effect of wind on tropospheric NO₂ columns had been found, while

wind direction determines how air from surrounding areas affected local pollution (Zhou et al. 2012). Exposure of precipitation also had a significant impact on NO₂; tropospheric NO₂ in general may decrease after precipitation (Zhou et al. 2012; Kim et al. 2014). NO₂ variability can also be influenced by ambient temperature, as higher temperatures contribute to shorter NO₂ lifetimes and lower tropospheric concentrations (Seinfeld and Pandis 2016). Meteorological data (temperatures at 2 m above Earth's surface, wind speed at 10 m above Earth's surface, and total precipitation) was taken from the European Center for Medium-Range Weather Forecasts Re-Analysis model (ERA5) reanalysis. ERA5 data have a spatial resolution of about 31 km.

Results and discussion

Since road transport and industry are the main sources of NO₂ emissions, the impact of lockdown restrictions on this main pollutant is expected to be severe and therefore easier to detect and quantify. Due to its short lifespan and relatively simple chemical composition, NO₂ is likely to be more influenced by meteorological conditions (Filonchyk et al. 2017, 2020; Bauwens et al. 2020; Goldberg et al. 2020; Pei et al. 2021). Changes in atmospheric pollutants largely depend on their emissions and meteorological conditions (Li et al. 2020). If the regional amount of emitted air pollutants is stable, then meteorological conditions can be a determining factor in the occurrence of air pollution (Gkatzelis et al. 2021; Shen et al. 2021). In this study, an attempt was made to compare meteorological conditions in different periods and their possible impact on NO₂ concentrations. However, this study does not account for the potential quantitative uncertainties associated with the impact of meteorology. There was made a comparison of meteorological parameters throughout the Central Asian countries in a 3-month period (March, April and May) with the same period in 2019. The data were averaged based on the average hourly ERA5 reanalysis data. The averaged wind speed and direction were estimated by taking into account the effects of winds on the tropospheric column concentration of NO₂ (Naeger and Murphy 2020) and are shown in Fig. 2, as well as air temperatures. Comparison of meteorological parameters in March, April, and May showed some differences (Table 1). Weather conditions in March 2020 were similar to 2019. The most noticeable differences in wind direction were observed over northern Kazakhstan, where winds shifted from the southeast direction in April 2020 compared to the 2019 period. In March, the average monthly temperature, wind speed, and total precipitation were about the same in all countries of the region. Total precipitation in all periods was also at the same level with slight fluctuations. In April and May, significant fluctuations in temperature and wind speed were observed.

Fig. 2 Spatial distribution of temperatures, wind speed, and wind vectors derived from the ERA5 reanalysis data between from March to May 2019 and 2020

Table 1 Monthly averages of meteorological conditions (temperature, wind speed, and total precipitation) from March to May 2020 and from March to May 2019 in five countries of Central Asia

	2019			2020			Difference		
	March	April	May	March	April	May	March	April	May
Temperature (°C)									
Kyrgyzstan	−2.83	3.03	5.80	−2.90	3.15	7.84	−0.07	0.12	2.04
Kazakhstan	1.14	9.01	16.64	1.42	11.05	19.08	0.28	2.04	2.44
Tajikistan	−4.56	1.92	4.58	−3.88	0.25	5.74	0.67	−1.68	1.16
Turkmenistan	11.60	16.13	25.32	11.82	16.54	24.76	0.21	0.42	−0.55
Uzbekistan	9.6	14.5	22.9	9.2	15.0	23.1	−0.4	0.6	0.2
Wind speed (m/s)									
Kyrgyzstan	1.36	4.50	2.71	1.60	3.04	3.34	0.24	−1.46	0.63
Kazakhstan	0.91	1.35	0.69	0.38	1.12	0.97	−0.53	−0.23	0.27
Tajikistan	2.22	4.24	1.39	1.86	3.17	2.34	−0.36	−1.06	0.95
Turkmenistan	1.68	1.89	0.39	0.94	1.34	0.53	−0.74	−0.55	0.14
Uzbekistan	1.46	1.94	0.48	0.76	1.47	1.32	−0.69	−0.47	0.83
Total precipitation (mm)									
Kyrgyzstan	1.50	1.56	1.57	1.53	1.54	1.55	0.03	−0.02	−0.02
Kazakhstan	4.10	3.94	4.06	4.31	4.13	4.16	0.21	0.19	0.10
Tajikistan	1.34	1.39	1.35	1.28	1.33	1.35	−0.06	−0.06	0.00
Turkmenistan	3.97	3.93	3.81	3.98	3.89	4.09	0.01	−0.04	0.29
Uzbekistan	3.66	3.73	3.77	4.22	3.71	3.75	0.56	−0.01	−0.02

Thus, in April, a decrease in wind speed was observed, but in May, on the contrary, it was slightly increased. Also, April and May 2020 are characterized by relatively higher temperatures compared to the same period in 2019, which could contribute to a more favorable environment for NO₂ decrease (Shikwambana et al. 2020). In general, the obtained meteorological conditions can be considered as conducive to the dispersion of pollutants, but not as the main factor influencing the air quality. Therefore, it can be concluded that the possible reduction in NO₂ concentrations during the study period cannot be strongly dependent on changes in meteorological conditions.

Satellites provide a unique, spatially continuous picture of air quality, which is usually not possible with a relatively sparse ground-based air quality monitoring network. Using such data, it is possible to compare the NO₂ levels in different periods. Significant spatiotemporal changes in NO₂ levels (before, during, and after the lockdown) over Central Asian countries are shown in Fig. 3. Analysis of tropospheric NO₂ concentration shows hot spots of high NO₂ values in places where urbanization or thermal power plants are located. The main sources of NO₂ emissions shown by TROPOMI coincide with the location of the largest thermal power plants in Kazakhstan and Uzbekistan. Those are Ekibastuz Power Plant 1 and 2, Aksu Power Plant, Zhambyl Power Plant located in the Pavlodar region in the north-east Kazakhstan with a total

power of more than 8000 Megawatt (MW). In Uzbekistan, hot spots of high concentrations are connected with Syrdarya TPP (thermal power plant) located in the Syrdarya region, Tashkent TPP, Novo-Angrenskaya TPP, and Angrenskaya TPP in Tashkent region, as well as Navoi TPP, the total capacity of which is more than 10,000 MW. Figure 3 shows that the locations of the emission hotspots were similar in 2019 and 2020, indicating continuous operation of thermal power plants in the period before, during, and after the lockdown, as they operated to meet the electricity demand.

Detailed analysis of NO₂ levels before, during, and after the lockdown shows a decrease in NO₂ levels in the region from −5.6 to −15.5%. Epicenters of high NO₂ values (more than 100 $\mu\text{mol}/\text{m}^2$) were registered in almost all countries of the region in both 2019 and 2020. As mentioned above, this is due to the thermal power plants located near the epicenters of high NO₂ values. Average concentration values in countries did not exceed 70 $\mu\text{mol}/\text{m}^2$ (Table 2). The largest decrease was in Kyrgyzstan and Kazakhstan, which may be due to tougher policies of containing the spread of the virus. On the contrary, in Turkmenistan, where initially the presence of COVID-19 cases was not recognized, reductions in NO₂ levels were the lowest. However, it is possible that a small part of the reduction may also be caused by meteorological variability (wind, temperature, cloud cover, and

Fig. 3 Spatial distribution of NO₂ and relative change (%) over Central Asian countries during 3 periods 2019–2020

Table 2 Tropospheric NO₂ concentrations (Max (mean ± SD)) (μmol/m²) and variation (%) over Central Asian countries

	2019			2020			Variation (%)		
	Before lock-down	During lockdown	After lock-down	Before lock-down	During lockdown	After lockdown	Before lockdown	During lockdown	After lockdown
Kyrgyzstan	217 (58 ± 12)	115 (63 ± 7)	116 (68 ± 6)	174 (49 ± 11)	107 (57 ± 7)	102 (60 ± 6)	− 15.5	− 9.5	− 11.8
Kazakhstan	373 (53 ± 10)	227 (63 ± 6)	158 (73 ± 6)	322 (46 ± 9)	150 (57 ± 5)	124 (64 ± 4)	− 13.2	− 9.5	− 12.3
Tajikistan	169 (56 ± 12)	144 (59 ± 9)	138 (65 ± 9)	159 (49 ± 13)	131 (56 ± 10)	145 (59 ± 8)	− 12.5	− 5.1	− 9.2
Turkmenistan	122 (61 ± 5)	102 (69 ± 4)	101 (72 ± 3)	126 (55 ± 6)	92 (61 ± 4)	98 (68 ± 3)	− 9.8	− 11.6	− 5.6
Uzbekistan	392 (66 ± 16)	300 (71 ± 11)	253 (74 ± 10)	371 (58 ± 20)	207 (63 ± 11)	158 (69 ± 7)	− 12.1	− 11.3	− 6.8

humidity), which can affect the transport and lifespan of NO_x (Bassani et al. 2021; Sahoo 2021).

Mobility data from Google report (Google 2020) during the lockdown period also indicate a decrease in restaurant visits, cafes, shopping malls, theme parks, museums, libraries, and cinemas for about − 66.4%, − 47.6%, and − 10.1%; reduction of visits to grocery stores, markets, specialty grocery stores, and pharmacies on − 53.4%, − 28.4%, and − 8.2%; reduction in the use of public transport by − 60.1%, − 35.5%, and − 16.3% in Kyrgyzstan, Kazakhstan, and Tajikistan. Nevertheless, the dynamics of movement in residential areas of Kyrgyzstan and Kazakhstan has increased by 19.4% and 14.8% from the baseline average.

The study shows that urban areas have experienced larger reductions in NO₂ concentrations than rural areas due to traffic restrictions and the suspension of some anthropogenic activities. These findings comply to the previous studies from different parts of the world (Filonchyk and Peterson 2020; Goldberg et al. 2020; Pacheco et al. 2020; Islam et al. 2021; Sahoo et al. 2020).

Column NO₂ over the capital cities and urban centers before and after the 2020 lockdown and similar periods in 2019 are shown in Fig. 4. The highest NO₂ concentrations were observed in Tashkent followed by Almaty and Bishkek (Table 3). It should be noted that these cities are the largest industrial and administrative centers of their countries. Figure 4 shows that practically in all cities of the region, a decrease in NO₂ concentration during the lockdown period was observed. Among large cities, Almaty experienced the largest decrease in NO₂ levels (− 34.2%) compared to the same period in 2019. Similar declines were observed in Karaganda (− 22.7%) and Tashkent (− 21.2%), while for other cities, the decline ranged from − 1.6 to − 16.5%. Many cities see greatest reduction of NO₂ in the period after lockdown, 9 of the 12 regions see the greatest reduction compared to 2019 during the after-lockdown phase. This may be due to the continuation of the restrictive measures introduced to combat the spread of the virus, as well as the economic consequences associated with the slowdown in economic growth in many countries, which subsequently affected the decline in economic activity and,

consequently, the emissions of pollutants into the atmosphere (Ryazantsev et al. 2020; Mele and Magazzino 2021).

Since NO₂ emissions are strongly associated with fuel combustion in the industrial and transport sectors, a decrease in activity of these sectors can lead to a significant decline in NO₂ concentrations.

The obtained results are consistent with the results carried out in other cities or regions. Filonchyk and Peterson (2020) reported of decreases in tropospheric NO₂ concentrations over Shanghai (China) during the lockdown compared to the same period in 2019. In Delhi, India, NO₂ concentrations were reduced by about 65.9% (Biswal et al. 2020). In the largest cities of Ecuador, Guayaquil, and Quito, during the lockdown period, the decrease in NO₂ concentration was 23.36% and 22.41% (Pacheco et al. 2020). Lockdown measures carried out in Iraq have resulted in a 35% to 40% decrease in NO₂ levels especially in Baghdad, Najaf, Basra, and Erbil (Hashim et al. 2021). Thus, the decrease in NO₂ concentration levels at different time intervals indicates the effectiveness of measures taken to stop the spread of the virus.

Air pollution is a complex problem which includes many factors. Reduction of pollutant emissions leads to improvements in air quality, but can also cause new problems associated with O₃ formation and secondary aerosol. Secondary pollutant formation mechanism should be studied to provide a more diverse scientific basis for the development of pollution prevention and control policies. Therefore, more studies are required to determine the impact of lockdown measures on various industries and its contribution into decline of NO₂ and other pollutant level. An on-site study will help to interpret the observed changes and evaluate the full impact of containment measures on air pollution.

Conclusions

Decreases in tropospheric NO₂ levels have been observed over most of the Central Asian countries. These reductions are mainly related to drastic measures taken to contain the

Fig. 4 Percentage change of tropospheric NO₂ during COVID-19 pandemic over capital cities and urban centers compared with same period 2019

Table 3 Mean and maximum concentrations (Max (mean ± SD)) and variations of tropospheric NO₂ (μmol/m²) over twelve selected cities over Central Asian countries before, during, and after lockdown

	2019			2020		
	Before lockdown	During lockdown	After lockdown	Before lockdown	During lockdown	After lockdown
Almaty	373 (243 ± 77)	227 (152 ± 37)	153 (115 ± 21)	322 (198 ± 70)	132 (100 ± 19)	117 (93 ± 13)
Nur-Sultan	98 (69 ± 11)	94 (79 ± 6)	118 (99 ± 9)	96 (70 ± 11)	77 (66 ± 5)	91 (77 ± 5)
Shymkent	142 (109 ± 14)	109 (91 ± 7)	121 (95 ± 10)	162 (110 ± 22)	120 (91 ± 12)	107 (83 ± 8)
Aktobe	64 (54 ± 3)	75 (63 ± 4)	100 (79 ± 4)	63 (51 ± 4)	72 (62 ± 3)	70 (63 ± 2)
Karaganda	102 (78 ± 10)	98 (88 ± 5)	115 (99 ± 8)	95 (84 ± 7)	81 (68 ± 5)	94 (80 ± 5)
Dushanbe	117 (94 ± 13)	88 (79 ± 5)	92 (85 ± 3)	103 (90 ± 8)	87 (80 ± 4)	82 (76 ± 3)
Namangan	150 (116 ± 15)	119 (103 ± 7)	120 (102 ± 8)	133 (110 ± 10)	98 (90 ± 4)	92 (84 ± 3)
Samarkand	125 (85 ± 17)	114 (84 ± 11)	112 (91 ± 9)	128 (77 ± 19)	84 (73 ± 5)	90 (77 ± 6)
Tashkent	392 (313 ± 45)	300 (217 ± 40)	253 (190 ± 38)	367 (275 ± 49)	207 (171 ± 22)	155 (130 ± 14)
Ashgabat	122 (110 ± 7)	102 (95 ± 4)	101 (95 ± 3)	126 (108 ± 9)	92 (86 ± 4)	98 (90 ± 4)
Bishkek	217 (170 ± 27)	113 (99 ± 8)	107 (94 ± 7)	174 (139 ± 17)	107 (90 ± 9)	91 (82 ± 5)
Osh	120 (114 ± 3)	97 (93 ± 2)	98 (95 ± 2)	108 (97 ± 5)	83 (80 ± 1)	80 (78 ± 1)

spread of COVID-19, which have led to significant reductions in vehicle exhaust emissions due to reduced traffic and some industrial activities. Also, a small proportion of NO₂ reduction may be related to meteorological factors. The study provided a baseline scenario that could assist relevant authorities in the future to control the air quality through policy reforms related to industrial and vehicle emissions.

Author contribution Zhongrong Zhang: supervision, methodology, formal analysis, investigation, writing — original draft; Yijia Liu: conceptualization, investigation, writing — review and editing; Haizhong Liu: methodology, resources, writing — original draft; Aihong Hao: validation, formal analysis; Zhongwei Zhang: methodology, validation, resources, software.

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Availability of data and material Data will be available on request.

Declarations

Ethics approval This article does not contain any studies with human participants or animals performed by any of the authors.

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