The impact of lockdown on nitrogen dioxide (NO$_2$) over Central Asian countries during the COVID-19 pandemic

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Abstract
Nitrogen dioxide (NO$_2$) 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 (NO$_2$) 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 NO$_2$ concentration in countries and major cities in the region. In particular, the obtained satellite data show a decreased tropospheric column of NO$_2$. 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$_x$ = NO$_2$ + NO) are among the main factors deteriorating the air quality due to their role as catalysts for the formation of ozone (O$_3$) 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$_2$ 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 11t 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 km$^2$ 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 (Indoitu et al. 2012; Shi et al. 2020). However, air quality studies have not been carried out during the pandemic.
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](image-url)
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 (± standard deviation (SD)) over the specified periods, with units in μmol/m². 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 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 NO$_2$ 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 NO$_2$ 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 NO$_2$ levels in different periods. Significant spatiotemporal changes in NO$_2$ levels (before, during, and after the lockdown) over Central Asian countries are shown in Fig. 3. Analysis of tropospheric NO$_2$ concentration shows hot spots of high NO$_2$ values in places where urbanization or thermal power plants are located. The main sources of NO$_2$ 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 NO$_2$ levels before, during, and after the lockdown shows a decrease in NO$_2$ levels in the region from $-5.6$ to $-15.5\%$. Epicenters of high NO$_2$ values (more than 100 $\mu$mol/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 NO$_2$ values. Average concentration values in countries did not exceed 70 $\mu$mol/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 NO$_2$ 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
humidity), which can affect the transport and lifespan of NOx (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% (Biswa1 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 NO$_2$ 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 NO$_2$ (μmol/m$^2$) over twelve selected cities over Central Asian countries before, during, and after lockdown

| City         | 2019 Before lockdown | 2019 During lockdown | 2019 After lockdown | 2020 Before lockdown | 2020 During lockdown | 2020 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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Consent for publication Not applicable.

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References

Atkinson RW, Butland BK, Anderson HR, Maynard RL (2018) Long-term concentrations of nitrogen dioxide and mortality: a meta-analysis of cohort studies. Epidemiology 29(4):460–472
Balakrishnan VS (2020) COVID-19 response in central Asia. The Lancet Microbe 1(7):e281
Bassani C, Vichi F, Esposito G, Montagnoli M, Giusto M, Iannello A (2021) Nitrogen dioxide reductions from satellite and surface observations during COVID-19 mitigation in Rome (Italy). Environ Sci Pollut Res 1-24. https://doi.org/10.1007/s11356-020-12141-9
Bauwens M, Compernolle S, Stavrakou T, Müller JF, Van Gent J, Eskes H, Zehner C (2020) Impact of coronavirus outbreak on NO2 pollution assessed using TROPOMI and OMI observations. Geophys Res Lett 47(11):e2020GL087978
Biswal A, Singh T, Singh V, Ravindra K, Mor S (2020) COVID-19 lockdown and its impact on tropospheric NO2 concentrations over India using satellite-based data. Heliyon 6(9):e04764
Chen BB, Sverdlik LG, Imashev SA, Solomon PA, Lantz J, Schauer JJ, Carmichael G (2013) Empirical relationship between particulate matter and aerosol optical depth over Northern Tien-Shan. Central Asia Air Qual Atmos Health 6(2):385–396
Debone D, da Costa MV, Miraglia SG (2020) 90 days of COVID-19 social distancing and its impacts on air quality and health in Sao Paulo. Brazil Sustainability 12(18):7440
Ding J, van der ARJ, Eskes HJ, Miyiling B, Stavrakou T, Van Geffen JHGM, Veekindt JP (2020) NOx emissions reduction and rebound in China due to the COVID-19 crisis. Geophys Res Lett 47(19):e2020GL089912
Dursun S, Sagdic M, Toros H (2021) The impact of COVID-19 measures on air quality in Turkey. Environ Forensics 1-13. https://doi.org/10.1007/19275922.2021.1892876
Eskes HJ, Eichmann KU (2020) S5P Mission Performance Centre Nitrogen Dioxide [L2__NO2__] Readme, document number: S5P-MPC-KNMI-PRF-NO2. 1.6, Royal Netherlands Meteorological Institute, De Bilt, The Netherlands, https://sentinels.copernicus.eu/web/sentinel/technical-guides/sentinel-5p/produ cts-algorithms
Filonchyk M, Hurynovich V, Yan H (2020) Impact of Covid-19 lockdown on air quality in the Poland Eastern Europe. Environ Res 198:110454
Filonchyk M, Hurynovich V, Yan H (2021) Impact of COVID-19 pandemic on air pollution in Poland based on surface measurements and satellite data. Aerosol Air Qual Res 21:200472–200472
Filonchyk M, Peterson M (2020) Air quality changes in Shanghai, China, and the surrounding urban agglomeration during the COVID-19 lockdown. J Geospatial Spat Anal 4(2):1–7
Filonchyk M, Yan H, Hurynovich V (2017) Temporal-spatial variations of air pollutants in Lanzhou, Gansu Province, China, during the spring-summer periods, 2014–2016: particulate matter from local sources and transported from deserts create air quality challenges. Environ Qual Manag 26(4):65–74
Goldberg DL, Annen MC, Griffin D, McLinden CA, Lu Z, Streets DG (2020) Disentangling the impact of the COVID-19 lockdowns on urban NO2 from natural variability. Geophys Res Lett 47(17):e2020GL089269
Google (2020) Google COVID-19 Community Mobility Reports. Accessed on 9th May. https://www.google.com/covid19/mobil ity/
Grange SK, Lee JD, Drysdale WS, Lewis AC, Hueglin C, Emmenegger L, Carslaw DC (2021) COVID-19 lockdowns highlight a risk of increasing ozone pollution in European urban areas. Atmos Chem Phys 21(3):4169–4185
Hashim BM, Al-Naseri SK, Al-Maliki A, Al-Ansari N (2021) Impact of COVID-19 lockdown on NO2, O3, PM2.5 and PM10 concentrations and assessing air quality changes in Baghdad Iraq. Sci Total Environ 754:141978
Hibbotson S (2020) COVID-19: Approaches, outlooks, and power dynamics in Central Asia. Asian Affairs 51(3):528–541
Indoitu R, Orlovsky L, Orlovsky N (2012) Dust storms in Central Asia: spatial and temporal variations. J Arid Environ 85:62–70
Islam MS, Tusher TR, Roy S, Rahman M (2021) Impacts of nationwide lockdown due to COVID-19 outbreak on air quality in Bangladesh: a spatiotemporal analysis. Air Qual Atmos Health 14:351–363
Jephcote C, Hansell AL, Adams K, Gulliver J (2021) Changes in air quality during COVID-19 ‘lockdown’in the United Kingdom. Environ Pollut 272:116011
Kerimray A, Baimatova N, Ibragimova OP, Bukenov B, Kenessov B, Plotitsyn P, Karaca F (2020) Assessing air quality changes in large cities during COVID-19 lockdowns: the impacts of traffic-free urban conditions in Almaty, Kazakhstan. Sci Total Environ 730:139179
Kim S, Hong KH, Jun H, Park YJ, Park M, Sunwoo Y (2014) Effect of precipitation on air pollutant concentration in Seoul, Korea. Asian J Atmos Environ 8(4):202–211
Li L, LQ, Huang L, Wang Q, Zhu A, Xu J, Chan A (2020) Air quality changes during the COVID-19 lockdown over the Yangtze River
Delta Region: an insight into the impact of human activity pattern changes on air pollution variation. Sci Total Environ 732:139282

Liu F, Page A, Strode SA, Yoshida Y, Choi S, Zheng B, Joiner J (2020) Abrupt decline in tropospheric nitrogen dioxide over China after the outbreak of COVID-19. Sci Adv 6(28):eabc2992

Liu J, Ding J, Li L, Li X, Zhang Z, Ran S, Wang J (2020) Characteristics of aerosol optical depth over land types in central Asia. Sci Total Environ 727:138676

Liu Y, Zhu Q, Wang R, Xiao K, Cha P (2019) Distribution, source and transport of the aerosols over Central Asia. Atmos Environ 210:120–131

Mele M, Magazzino C (2021) Pollution, economic growth, and COVID-19 deaths in India: a machine learning evidence. Environl Sci Pollut Res 28(3):2669–2677

Menut L, Bessagnet B, Siour G, Mailler S, Pennel R, Cholakian A (2020) Impact of lockdown measures to combat Covid-19 on air quality over western Europe. Sci Total Environ 741:140426

Ming W, Zhou Z, Ai H, Bi H, Zhong Y (2020) COVID-19 and air quality: evidence from China. Emerg Mark Finance Trade 56(10):2422–2442

Naeger AR, Murphy K (2020) Impact of COVID-19 containment measures on air pollution in California. Aerosol Air Qual Res 20(10):2025–2034

Pacheco H, Díaz-López S, Jarre E, Pacheco H, Méndez W, Zamora-Ledesma E (2020) NO2 levels after the COVID-19 lockdown in Ecuador: a trade-off between environment and human health. Urban Clim 34:100674

Pei L, Wang X, Guo B, Guo H, Yu Y (2021) Do air pollutants as well as meteorological factors impact Corona Virus Disease 2019 (COVID-19)? Evidence from China based on the geographical perspective. Environ Sci Pollut Res 28:35584–35596

Ryazantsev SV, Vazirov ZK, Khramova MN, Smirnov AV (2020) The impact of the COVID-19 pandemic on the position of labor migrants from Central Asia in Russia. Central Asia and the Caucasus 21(3):58–70

Sahoo MM (2021) Significance between air pollutants, meteorological factors, and COVID-19 infections: probable evidences in India. Environ Sci Pollut Res 28:40474–40795

Sahoo PK, Chauhan AK, Mangla S, Pathak AK, Garg VK (2020) COVID-19 pandemic: an outlook on its impact on air quality and its association with environmental variables in major cities of Punjab and Chandigarh, India. Environ Forensics 22(1–2):143–154

Sasidharan M, Singh A, Torbaghan ME, Parlikad AK (2020) A vulnerability-based approach to human-mobility reduction for countering COVID-19 transmission in London while considering local air quality. Sci Total Environ 741:140515

Gkatzelis GI, Gilman JB, Brown SS, Eskes H, Gomes AR, Lange AC, Kiendler-Scharr A (2021) The global impacts of COVID-19 lockdowns on urban air pollution: a critical review and recommendations. Elem Sci Anth 9(1):00176

Shah V, Jacob DJ, Li K, Silvern RF, Zhai S, Liu M, Zhang Q (2020) Effect of changing NO x lifetime on the seasonality and long-term trends of satellite-observed tropospheric NO2 columns over China. Atmos Chem Phys 20(3):1483–1495

Shi L, Zhang J, Yao F, Zhang D, Guo H (2020) Temporal variation of dust emissions in dust sources over Central Asia in recent decades and the climate linkages. Atmos Environ 222:117176

Shikwambana L, Mhangara P, Mbatu N (2020) Trend analysis and first time observations of sulphur dioxide and nitrogen dioxide in South Africa using TROPOMI/Sentinel-5 P data. Int J Appl Earth Obs Geoinformation 91:102130

Sidic P, De Marco A, Agathokleous E, Feng Z, Xu X, Paoletti E, Calatauy V (2020) Amplified pollution in cities during the COVID-19 lockdown. Sci Total Environ 735:139542

Van Geffen J, Boersma KF, Eskes H, Snee M, Ter Linden M, Zara M, Vreekind JP (2020) 5P TROPOMI NO2 slant column retrieval: method, stability, uncertainties and comparisons with OMI. Atmos Meas Tech 13(3):1315–1335

Vreekind JP, Aben I, McMullan K, Förster H, De Vries J, Otter G, Levelt PF (2012) TROPOMI on the ESA Sentinel-5 Precursor: a GMES mission for global observations of the atmospheric composition for climate, air quality and ozone layer applications. Remote Sens Environ 120:70–83

Wang D, Zhang F, Yang S, Xia N, Ariken M (2020a) Exploring the spatial-temporal characteristics of the aerosol optical depth (AOD) in Central Asia based on the moderate resolution imaging spectroradiometer (MODIS). Environ Monit Assess 192:1–15

Wang L, Li M, Yu S, Chen X, Li Z, Zhang Y, Seinfeld JH (2020b) Unexpected rise of ozone in urban and rural areas, and sulfur dioxide in rural areas during the coronavirus city lockdown in Hangzhou, China: implications for air quality. Environ Chem Lett 18(5):1713–1723

Wünning JA, Wünning JG (1997) Flameless oxidation to reduce thermal NO-formation. Prog Energy Combust Sci 23(1):81–94

Zhang XX, Claiborn C, Lei JQ, Vaughan J, Wu SX, Li SY, Zhou J (2020) Aeolian dust in Central Asia: spatial distribution and temporal variability. Atmos Environ 238:117734

Zhou Y, Brunner D, Haeuglin C, Henne S, Staehelin J (2012) Changes in OMI tropospheric NO2 columns over Europe from 2004 to 2009 and the influence of meteorological variability. Atmos Environ 46:482–495

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