Aerosol and Air Quality
Research

ORIGINAL RESEARCH
https://doi.org/10.4209/aaqr.220196

Assessment of COVID-19 Impacts on Air Quality in Ulaanbaatar, Mongolia, Based on Terrestrial and Sentinel-5P TROPOMI Data

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ABSTRACT

The study aims to reveal the impact of three sequential strict-lockdowns of COVID-19 measures on the air pollutants including NO_2, SO_2, PM_{10}, and $PM_{2.5}$ in Ulaanbaatar, Mongolia during November 2020–February 2021 based on air quality network and satellite data. Based on measurements of automatic air quality sites in Ulaanbaatar, we found a substantial decrease in NO_2 (up to 45%), PM_{10} (72%), and $PM_{2.5}$ (59%) compared to the same periods in the previous five years. On the other hand, up to a threefold increase in SO_2 concentration was seen. Compared to 2015–2020, the number of days exceeding the national air quality standard level of NO_2 decreased by 55% during November 2020–February 2021. A similar trend was observed for PM_{10} and $PM_{2.5}$ (30% and 14%, respectively). Conversely, days exceeding the national air quality standard level of SO_2 increased by 58%. The third strict-lockdown exhibited significant reductions in pollutant concentrations. The percentage exceeding the national standard level for NO_2, PM_{10}, and $PM_{2.5}$ constituted 23%, 50%, and 67% during the lockdown periods while it was 89%, 84%, and 91%, respectively, for the same periods in the previous five years. Even though Sentinel 5P-TROPOMI data do not fully reflect the above findings, they add valuable insights into the spatial pollution pattern during strict-lockdown and non-lockdown periods. The study demonstrates that measures taken during the strict-lockdown periods clearly influenced the values of daily patterns of NO_2, PM_{10}, and $PM_{2.5}$ concentrations. On the contrary, it is important to note that SO_2 concentration increased during the last two winter months after 2019.

Keywords: Air pollution, Strict lockdown, COVID-19, Ulaanbaatar

1 INTRODUCTION

COVID-19 and air pollution are linked in at least two ways. On the one hand, lockdowns often led to reductions in traffic and industrial production, and thus a reduction in air pollution. On the other hand, exposure to air pollution has been identified as a factor that aggravates the course of COVID-19 infections.

1.1 Impacts of COVID-19 on Global Air Pollution

The lockdowns introduced in about 140 countries to slow down the spread of COVID-19

OPEN ACCESS

Received: May 14, 2022
Revised: July 10, 2022
Accepted: August 18, 2022

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Publisher:
Taiwan Association for Aerosol Research
ISSN: 1680-8584 print
ISSN: 2071-1409 online

constitute the largest quarantine policy in the history of public health (Liu *et al.*, 2021a), and led to unprecedented declines in land and air transportation and economic activities (Venter *et al.*, 2021). The following lockdown measures potentially contributed to changes in air quality: (1) internal travel restrictions (domestic and within certain cities); (2) international travel restrictions; (3) closure of public transport systems; (4) (partial) shutdown of industry; (5) stay-at-home requirements and (6) contact limitations, e.g., through closure of shops, kindergartens, schools and universities, cancellation of events, restrictions on meetings and gatherings (Liu *et al.*, 2021a). At the global level, daily $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO concentrations decreased during lockdown periods. The greatest reductions (23 to 60%) were observed for NO_2, mostly due to restrictions on intracity travel, and for PM (by 7% to 45%). Reductions were almost negligible for SO_2, which is typically emitted by industry and energy production, and O_3 concentrations were slightly higher during lockdowns as compared to reference periods (Liu *et al.*, 2021a; Venter *et al.*, 2021). In Italy, the worst-affected country during the first wave of the pandemic, strict lockdowns were imposed from March 2020 onwards. While NO_2 concentrations dropped remarkably in cities throughout Italy (by 25% to 59%), $PM_{2.5}$ concentrations mostly decreased but partially also increased, presumably due to increased domestic heating (Gualtieri *et al.*, 2020). In the UK, the implementation of a lockdown at the end of March 2020 induced an abrupt reduction in NO_2, NO, and NO_x at urban roadside monitoring stations, but a gradual return of traffic offset more than half of the reductions by summer 2020 (Ropkins and Tate, 2021). Menut *et al.* (2020) cautioned that different meteorological conditions and a general decrease in air pollution in western Europe make direct comparisons difficult. Nevertheless, through a modelling approach that considered meteorology and general air pollution trends, the authors confirmed that NO_2 strongly and PM moderately decreased due to the lockdowns (Menut *et al.*, 2020). In the US, Son *et al.* (2020) showed that in 10 states, regions with high baseline levels of air pollution experienced the largest air quality improvements following travel and other restrictions.

Improvement in air quality due to lockdowns could also be noticed in Asian countries. Many countries in the region, particularly India and China, experienced a strong rise in air pollution as a consequence of their economic development that went along with increasing fossil fuel consumption in industry and transportation (Smith *et al.*, 2001; Streets *et al.*, 2003; Zhao *et al.*, 2008; Smith *et al.*, 2011; Chin *et al.*, 2014). The core findings of case studies from East and Central Asia are summarized in Table 1. Changes in pollutant concentrations in the table have been rounded to whole numbers. It is important to note that the term "lockdown" refers to a wide range of restrictions, including those in mobility (up to curfews) and partial to full shutdowns of industrial production. Governments have also introduced different terminologies to refer to such periods, including COVID19 control policies, COVID-19 emergency responses, movement control orders, large-scale social restrictions and shutdowns. As the exact character of lockdowns and their implementation has often not been documented in detail, and papers are based on different numbers and durations of lockdown events and reference periods, the information provided should be considered as indicative values for the range of changes observed across Asia. In addition, it should be noted that a direct comparison between the different data is not meaningful since the studies did not only differ in methodologies, but also regarding the lockdown periods (timing, duration, and strength of the lockdown) and the reference periods against which the reductions have been calculated. Nevertheless, data from all countries, regions, and cities show lockdown-related reductions in air pollution.

Reductions in air pollution were observed not only over land but also in close proximity to pollution sources. Griffith *et al.* (2020) showed that long-range transport (LRT) of air pollutants from East Asia was approximately 50% less than during normal periods, especially from China. For South East Asia, Kanniah *et al.* (2020) reported a 27% to 30% reduction in NO_2 outflow over oceanic regions.

1.2 Impacts of Air Pollution on COVID-19 Pathogenesis

Even though the combined health impacts of air pollution and COVID-19 are not yet fully understood, several recent studies showed that air pollution appears to aggravate the risks related to COVID-19 infections (Srivastava, 2021). This is plausible since air pollution is known to be the cause of several respiratory illnesses such as chronic obstructive pulmonary disorder (COPD),

Table 1. Findings of case studies on the impacts of lockdowns on air pollution.

Country/Region	Impact of lockdowns on air pollution	Source
East Asia		
China	20% to 40% reduction in NO_2 in Eastern provinces	Acharya *et al.*, 2021
	Up to 83% reduction in NO_2 in Wuhan	Ghahremanloo *et al.*, 2021
	10% to 20% reduction in $PM_{2.5}$ nationwide	Wang *et al.*, 2020b
	Largest effects in northern and eastern parts of China, particularly in highly industrialized and relatively wealthy cities	Wang *et al.*, 2020a
	For Beijing:	Fu *et al.*, 2020
	42% reduction in NO_2	
	60% reduction in SO_2	
	15% reduction in $PM_{2.5}$	
	0% reduction in PM_{10}	
	For Wuhan:	Li and Xu, 2021
	63% reduction in NO_2	
	29% reduction in SO_2	
	26% reduction in $PM_{2.5}$	
	32% reduction in PM_{10}	
	For Hangzhou:	Liu *et al.*, 2021b
	77% reduction in NO_2	
	18% reduction in SO_2	
	50% reduction in $PM_{2.5}$	
	50% reduction in PM_{10}	
	24% reduction in CO	
Japan	Up to 19% reduction in NO_2 in Tokyo	Ghahremanloo *et al.*, 2021
	For Tokyo:	Fu *et al.*, 2020
	26% reduction in NO_2	
	38% reduction in SO_2	
	23% reduction in $PM_{2.5}$	
	24% reduction in PM_{10}	
South Korea	Up to 33% reduction in NO_2 in Seoul	Ghahremanloo *et al.*, 2021
	For Seoul:	Fu *et al.*, 2020
	28% reduction in NO_2	
	28% reduction in SO_2	
	21% reduction in $PM_{2.5}$	
	9% reduction in PM_{10}	
	For Seoul:	Park *et al.*, 2021
	44% reduction in $PM_{2.5}$ caused by a combination of more active local wind circulation, less need for heating, partial lockdown and implementation of guidelines aimed at PM reduction	
Central Asia		
Iran	Notable reductions in CO, NO_2, SO_2, and PM	Broomandi *et al.*, 2020
Kazakhstan	6% to 34% reduction in $PM_{2.5}$ in Almaty	Kerimray *et al.*, 2020
	For Ust-Kamenogors (= Oskemen):	Assanov *et al.*, 2021
	13 to 21% increase in PM	
	No significant change in NO_2 and SO_2	
China	For Inner Mongolia:	Chen *et al.*, 2020
	12% reduction in $PM_{2.5}$	
	18% reduction in PM_{10}	
	8% reduction in NO_2	
	16% reduction in SO_2	
	Note – this publication covers all provinces of China.	

Table 1. (*continued*).

Country/Region	Impact of lockdowns on air pollution	Source
South Asia		
Bangladesh	For Dhaka:	Islam *et al.*, 2021
	17% reduction in $PM_{2.5}$	
	17% reduction in NO_2	
	11% reduction in SO_2	
India	20% to 40% reduction in NO_2	Acharya *et al.*, 2021
	For the state of Gujarat:	Selvam *et al.*, 2020
	30% to 84% reduction in NO_2	
	22% to 58% reduction in SO_2	
	34% to 78% reduction in $PM_{2.5}$	
	47% to 80% reduction in PM_{10}	
	For Kolkata:	Chowdhuri *et al.*, 2020
	51% reduction in PM_{10}	
	68% reduction in NO_2	
	40% reduction in SO_2	
	For Delhi:	Kumari *et al.*, 2020
	58% reduction in NO_2	
	24% reduction in SO_2	
	31% reduction in $PM_{2.5}$	
	48% reduction in PM_{10}	
	For Delhi:	Bedi *et al.*, 2020
	64% reduction in $PM_{2.5}$	
	57% reduction in PM_{10}	
	64% reduction in NO_2	
	8.9% reduction in SO_2	
	For Mumbai:	
	35% reduction in $PM_{2.5}$	
	20% reduction in PM_{10}	
	74% reduction in NO_2	
	32% increase in SO_2	
	For Kolkata:	
	54% reduction in $PM_{2.5}$	
	34% reduction in PM_{10}	
	66% reduction in NO_2	
	23% reduction in SO_2	
	For Chennai:	
	9% increase in $PM_{2.5}$	
	29% reduction in NO_2	
	5% reduction in SO_2	
	For cities in Uttar Pradesh:	
	45% reduction in $PM_{2.5}$	
	For 5 different locations in Chennai:	Singh and Tyagi, 2021
	34 to 56% reduction in NO_x	
	94% reduction to 72% increase in SO_2	
	24% to 65% reduction in $PM_{2.5}$	
	Across India:	Verma and Kamyotra, 2021
	33% reduction in PM_{10}	
	47% reduction in NO_2	
	21% reduction in SO_2	
Pakistan	For Lahore: 32% reduction in NO_2	Shafeeque *et al.*, 2021
	For Karachi: 26% reduction in NO_2	
	Across Pakistan: 7% reduction in $PM_{2.5}$	Khan *et al.*, 2021

Table 1. (*continued*).

Country/Region	Impact of lockdowns on air pollution	Source
Southeast Asia		
South East Asia	20% to 40% reduction in NO_2	Acharya *et al.*, 2021
Indonesia	For Jakarta: 40% reduction in $PM_{2.5}$ Decrease in black carbon, NO_x and SO_2	Santoso *et al.*, 2021
Malaysia	26% to 31% reduction in PM_{10} 23% to 32% reduction in $PM_{2.5}$ 63% to 64% reduction in NO_2 9% to 20% reduction in SO_2 25% to 31% reduction in CO	Kanniah *et al.*, 2020
	For Klang Valley (Greater Kuala Lumpur): 17 o 36% reduction in $PM_{2.5}$ 49 to 68% reduction in NO_2 6 to 26% reduction in SO_2	Suhaimi *et al.*, 2020
Thailand	For Bangkok: 16% reduction in $PM_{2.5}$	Wetchayont *et al.*, 2021
	Increased NO_2 and SO_2 concentrations Reductions in CO, O_3 and $PM_{2.5}$ were also observed during the "new normal" after the lockdowns For Bangkok – road sites: 11% reduction in $PM_{2.5}$ 8% reduction in NO_2	Dejchanchaiwong and Tekasakul, 2021
	For Bangkok - business areas: 17% increase in $PM_{2.5}$ 13% reduction in NO_2 Across Thailand: 10% reduction in NO_2 during curfews	Oo *et al.*, 2021
	For Bangkok: 20% reduction in NO_2 during curfews In the Hat Yai area: 34% reduction in NO_2 22% reduction in $PM_{2.5}$ 23% reduction in PM_{10}	Stratoulias and Nuthammachot, 2020
Vietnam	For Hanoi: 14 to 18% reduction in $PM_{2.5}$ (7 to 10% weather-normalized reduction)	Le *et al.*, 2021

cancer, and infections of the lung, but also to compromised immune systems (Gupta *et al.*, 2021). A study in the Netherlands showed that $PM_{2.5}$, NO_2, and SO_2 concentrations in 355 municipalities correlated positively with registered COVID-19 cases, hospital admissions and deaths due to COVID-19 (Cole *et al.*, 2020). Exposure to air pollution has in general been found to increase viral infections of the respiratory tract (Travaglio *et al.*, 2021; Conticini *et al.*, 2020). According to Setti *et al.* (2020), particulate matter can actually be a carrier of the COVID-19 virus. Research on urban air pollution in cities of China, India, Indonesia, and Pakistan revealed that long-term exposures to high air pollution, particularly to $PM_{2.5}$, negatively impacted the outcomes of COVID-19 infections. The mortality rate associated with COVID-19 is significantly correlated with $PM_{2.5}$ ($p < 0.05$), which is responsible for most of the air pollution-related deaths in the world (Gupta *et al.*, 2021). Copat *et al.* (2020) found that $PM_{2.5}$ and NO_2 concentrations were more closely correlated to the spread and lethality of COVID-19 than PM_{10}. Filippini *et al.* (2021) showed for two regions of Italy that NO_2 concentrations correlated positively with COVID-19 severity. In a study on COVID-19 mortality in 66 administrative regions in Italy, Spain, France, and Germany, Ogen (2020) found 78% of the deaths to have occurred in those five regions that had the highest NO_2 concentrations and concluded that long-term exposure to this pollutant may be one of the most important contributors to COVID-19 fatality. According to Karuppasamy *et al.* (2020), improvements in air quality can therefore have the co-benefit to reduce mortality directly and indirectly (via reducing the risks associated with COVID-19 infections).

1.3 COVID-19 Measures Taken in Mongolia

According to the Law on Disaster Protection (Mongolian Parliament, 2003), the disaster preparedness regime in Mongolia is divided into three levels—daily preparedness, enhanced readiness, and public emergency readiness. Mongolia went into the state of "enhanced readiness" level on February 11, 2020. The precautionary measures of the "enhanced readiness" level include travel restrictions, partial remote work from home, school closings, and restrictions in public activities. The first positive case of coronavirus, who arrived in Mongolia via an international flight was reported on March 10, 2020 (Erkhembayar *et al.*, 2020). On November 10, 2020, the first case of community transmission from an individual arriving from Russia was registered. After the patient was released from isolation for 21 days, Mongolia's State Emergency Committee (SEC) announced the "public emergency readiness" level (or strict-lockdown) measures: all services and businesses except essential sectors were closed to work from home, the stay-at-home regime was activated, all international and domestic traffic beyond city boundaries was temporarily suspended, public gatherings suspended, and all levels of educational institutions are closed. In order to prevent the spread of coronavirus, three periods (a total of 63 days) of strict-lockdown periods were set from November 2020 to February 2021 (see Table 5).

According to Shrestha *et al.* (2020), declines in air pollutant concentrations up to 43% related to COVID-19 lockdowns in Ulaanbaatar were reported. However, there was no mention of the combined reason for the declines which is indeed related to change in fuel type since winter of 2019-2020 and seasonal variations of the pollutants. The winter of 2019–2020 was characterized by substantial declines in $PM_{2.5}$ and PM_{10} concentrations due to the transition from raw coal to briquette fuel in Ulaanbaatar (Ganbat *et al.*, 2020). The current study investigates the effect of COVID-19 strict lockdowns on air pollutants in Ulaanbaatar, Mongolia, using terrestrial and satellite observations.

2 MATERIALS AND METHODS

2.1 Study Area

Ulaanbaatar, the capital of Mongolia, is located in a valley between the Bogd Khan mountain in the south and the extensions of the Khentii Mountains in the north (Fig. 1) at an approximate altitude of 1300 m above sea level. Ulaanbaatar has a population of nearly 1.5 million inhabitants, accounting for 47% of the total population of Mongolia. Ulaanbaatar is known as the 'coldest capital' in the world with winter temperatures often dropping below –20°C and the cold weather in winter is attributed to the Siberian high-pressure system, which causes the formation of a temperature inversion (Ganbat and Baik, 2016). In poor vertical mixing under the weather condition with temperature inversions, the majority of pollutant sources is crustal matter and coal combustion (Davy *et al.*, 2011) from ger areas, where around half of the Ulaanbaatar's population lives (Karthe *et al.*, 2022). Heating in ger areas during the heating season is supplied by fuel-stoves. After a decade of the severe air pollution problem, a notable reduction in air pollution in Ulaanbaatar is seen after introducing upgraded briquette fuel since winter 2019–2020 (Ganbat *et al.*, 2020; Soyol-Erdene *et al.*, 2021). However, the PM concentrations in winter 2019–2020 still exceeded the national air quality standard levels.

2.2 Terrestrial Data

Concentrations of air pollutants—NO_2, SO_2, PM_{10}, and $PM_{2.5}$, which are commonly used to assess air quality, are used in this study to investigate the effects of COVID-19 measures on air quality in Ulaanbaatar. Data from 1 January 2015 to 1 March 2021 were obtained from 12 air quality monitoring sites located at various points in Ulaanbaatar (Fig. 1 and Table 2). The sites are operated by the National Agency for Meteorology and Environmental Monitoring (NAMEM) and the Air Pollution Reduction Department (APRD) of the Municipality.

According to the current national air quality standard, MNS 4585:2016, which is amended in 2016, the national standard levels of 24-h NO_2, SO_2, PM_{10}, and $PM_{2.5}$ are set 50 µg m^{-3}, 50 µg m^{-3},

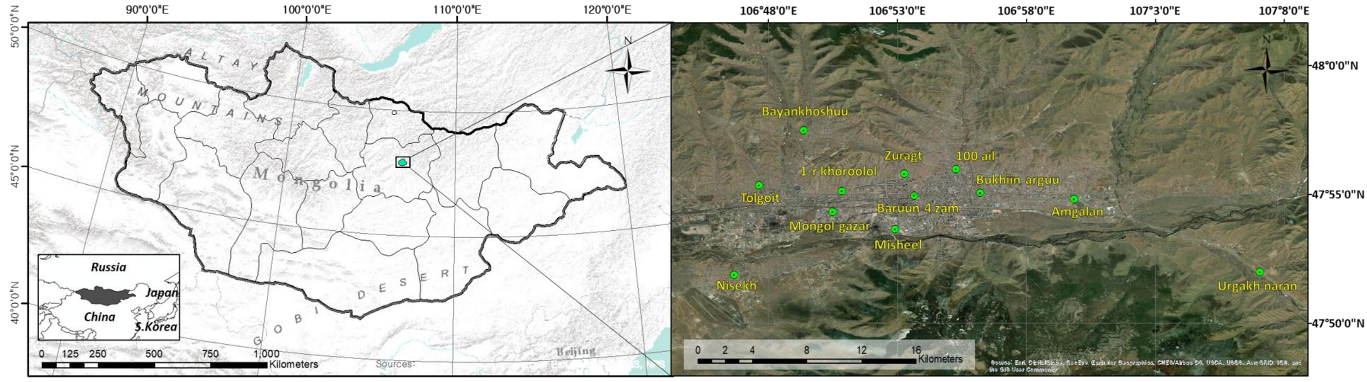


Fig. 1. Air quality monitoring sites in Ulaanbaatar.

Table 2. Air quality monitoring sites in Ulaanbaatar and measuring pollutants.

Site name	Location	NO_2	SO_2	PM_{10}	$PM_{2.5}$
Misheel	47°53’38.4”N, 106°52’55.92”E	+	+	+	-
Baruun 4 zam	47°54’55.8”N, 106°53’40.2”E	+	+	+	+
1-r khoroolol	47°55’7.68”N, 106°50’52.08”E	+	+	+	+
Bukhiin urguu	47°55’3.36”N, 106°56’15”E	+	+	+	+
100 ail	47°55’58.8”N, 106°55’17.04”E	+	+	+	-
Mongol gazar	47°54’18.36”N, 106°50’30.84”E	+	+	+	-
Urgakh naran	47°51’59.4”N, 107°7’4.8”E	+	-	+	-
Tolgoit	47°55’20.28”N, 106°47’39.84”E	+	+	+	+
Zuragt	47°55’47.28”N, 106°53’17.88”E	+	+	+	+
Amgalan	47°54’48.6”N, 106°59’52.8”E	+	+	+	+
Nisekh	47°51’51.84”N, 106°46’41.88”E	+	+	+	+
Bayankhoshuu	47°57’28.08”N, 106°49’22.8”E	-	+	+	+

100 μg m^{-3}, and 50 μg m^{-3}, respectively. The annual standard levels of NO_2, SO_2, PM_{10}, and $PM_{2.5}$ are 40 μg m^{-3}, 20 μg m^{-3}, 50 μg m^{-3}, and 25 μg m^{-3}, respectively.

2.3 Air Pollution Monitoring by Remote Sensing

Meteorological satellites have been able to monitor atmospheric water vapor content since the early 1970s, and the Advanced Very-High-Resolution Radiometer (AvHRR) sensors have provided global information on the occurrence and distribution of aerosols since 1981 (Stowe *et al.*, 2002; Zhang *et al.*, 2020). The introduction of the Global Ozone Measurement Experiment (GOME) spectrometer aboard the ERS-2 satellite in 1995, and the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) aboard the ENVISAT satellites since 2002 significantly widened the potential of satellite remote sensing for air pollution monitoring as it provided information on aerosols and a wide range of trace gases including NO_2, SO_2 and several others (Bovensmann *et al.*, 1999; Noël *et al.*, 2003). Further improvements in spectral, radiometric, spatial, and temporal resolution have been realized with the TROPOspheric Monitoring Instrument (TROPOMI) aboard the Sentinel 5 Precursor satellite. It allows the monitoring of temporal changes and assessment of long-term trends in atmospheric chemistry. It can quantify aerosols and several trace gases including NO_2, O_3, SO_2, CO, CH_4, and CH_2O. TROPOMI is based on a UVNS (UV–VIS–NIR–SWIR) spectrometer that scans an approximately 2600 km wide swath, along which it moves at a speed of 7 km s^{-1}. It offers a daily coverage at a spatial resolution of 7 km × 7 km in most bands, and 21 km × 28 km in the UV band (Veefkind *et al.*, 2012). The accuracy and precision of the TROPOMI instrument for the parameters considered in this study are shown in Table 3.

China has recently developed into another major operator of satellites capable of air pollution monitoring, including aerosols, NO_2, SO_2, and several other pollutants (Zhang *et al.*, 2020). Remote sensing-based approaches have contributed to air quality assessments at various scales ranging

Table 3. Accuracy and precision of the TROPOMI measurements.

Parameter		NO_2	SO_2	Aerosol
Accuracy	TC	10%	2 DU	
	AC	10^{15} mol cm^{-2}		
	OT			0.1 (20%)
Precision	TC	10^{15} mol m^{-2}	1 DU	
	AC	10^{15} mol cm^{-2}		
	OT			0.05 (10%)

TC: tropospheric column; AC: total atmospheric column; OT: optical thickness; DU: Dobson units (1 DU = 2.69 × 1016 molecules per cm^2)

from local studies—often in affected cities— (e.g., Huang *et al.*, 2021; Prunet *et al.*, 2020) to regional and national-level investigations (e.g., Shikwambana *et al.*, 2020; Stratoulias and Nuthammachot, 2020; Zheng *et al.*, 2019) and global studies (e.g., Lim *et al.*, 2020). Particularly, studies focusing on NO_2 to thoroughly understand the effects of the COVID-19 lockdown on the atmosphere are gaining popularity (e.g., Scheibenreif *et al.*, 2021; Vîrghileanu *et al.*, 2020; Wang *et al.*, 2021). This study uses TROPOMI NO_2 spatial variations as an extension to illustrate changes in several pollutants during the COVID-19 strict and non-strict lockdown periods.

3 RESULTS AND DISCUSSION

The time series of daily mean NO_2, SO_2, PM_{10}, and $PM_{2.5}$ concentrations from January 2015 to March 2021 averaged over the air quality monitoring sites in Ulaanbaatar are shown in Fig. 2. In general, decreasing trends in NO_2, PM_{10}, and $PM_{2.5}$ after winter 2019–2020 can be clearly seen. The pollutant concentrations show that the main air pollutants in Ulaanbaatar were PM_{10} and $PM_{2.5}$ before the winter of 2019–2020. The concentrations of all pollutants have strong seasonal patterns. The winter of 2020–2021 was the period with the lowest PM_{10} (108.5 ± 36.2 µg m^{-3}) and $PM_{2.5}$ (76.0 ± 38.9 µg m^{-3}) since 2016. On the contrary, it is clearly seen that SO_2 concentrations significantly increased in the last two winters.

A decrease in yearly-mean NO_2 concentration of 17% was observed in 2020 compared to the mean of 2015–2019. The decreasing trend is mild for the yearly values but more pronounced in winter. An increasing trend in SO_2 concentrations is observed in winters after 2019–2020. An increase in SO_2 concentration of 79% was observed in 2020 compared to 2015–2019 mean and 2.7 times higher than the national standard value of 20 µg m^{-3}.

A decrease in PM_{10} concentration of 24% was observed in 2020 compared to the 2015–2019 mean. However, the annual PM_{10} concentration still exceeds the national standard value of 50 µg m^{-3}. Decrease in $PM_{2.5}$ concentration of 51% was observed in 2020 compared to 2015–2019 mean. Comparisons of PM_{10} and $PM_{2.5}$ concentrations between before and after the 2019–2021 winters show decreased trends while SO_2 concentration showed a notable increased trend. Specifically, SO_2 concentrations in winters 2019–2020 and 2020–2021 are steadily increased. The reason for the increased SO_2 concentration could be attributed to contents of the briquette fuel consumed in households in ger areas since 2019 and the increased demand in consumption of briquette fuel in households due to stay-at-home activity. In line with a previous study by Ganbat *et al.* (2020), the immediate reductions of PM_{10} and $PM_{2.5}$ in winter 2019–2020 are related to the change in fuel type. Thus, the declines in PM_{10} and $PM_{2.5}$ in winter 2020–2021 are likely attributed to the combined effects of measures of the transition from raw coal to upgraded briquette fuel and the effects of the COVID-19 strict-lockdowns.

The combined effects of this source change and weather condition may affect the changes in pollutant concentrations. To mention, according to official reports released by the NAMEM, the weather condition during the winter 2020–2021 was not peculiar (www.tsag-agaar.mn). The weather condition in the winter 2020–2021 showed the similar characteristics compared to the previous winters—low wind speed and temperature similar to previous years. To clearly see the impacts of strict-lockdowns to air pollution, the periods of strict-lockdowns and non-lockdowns are compared (please see Table 5 and Fig. 5 later).

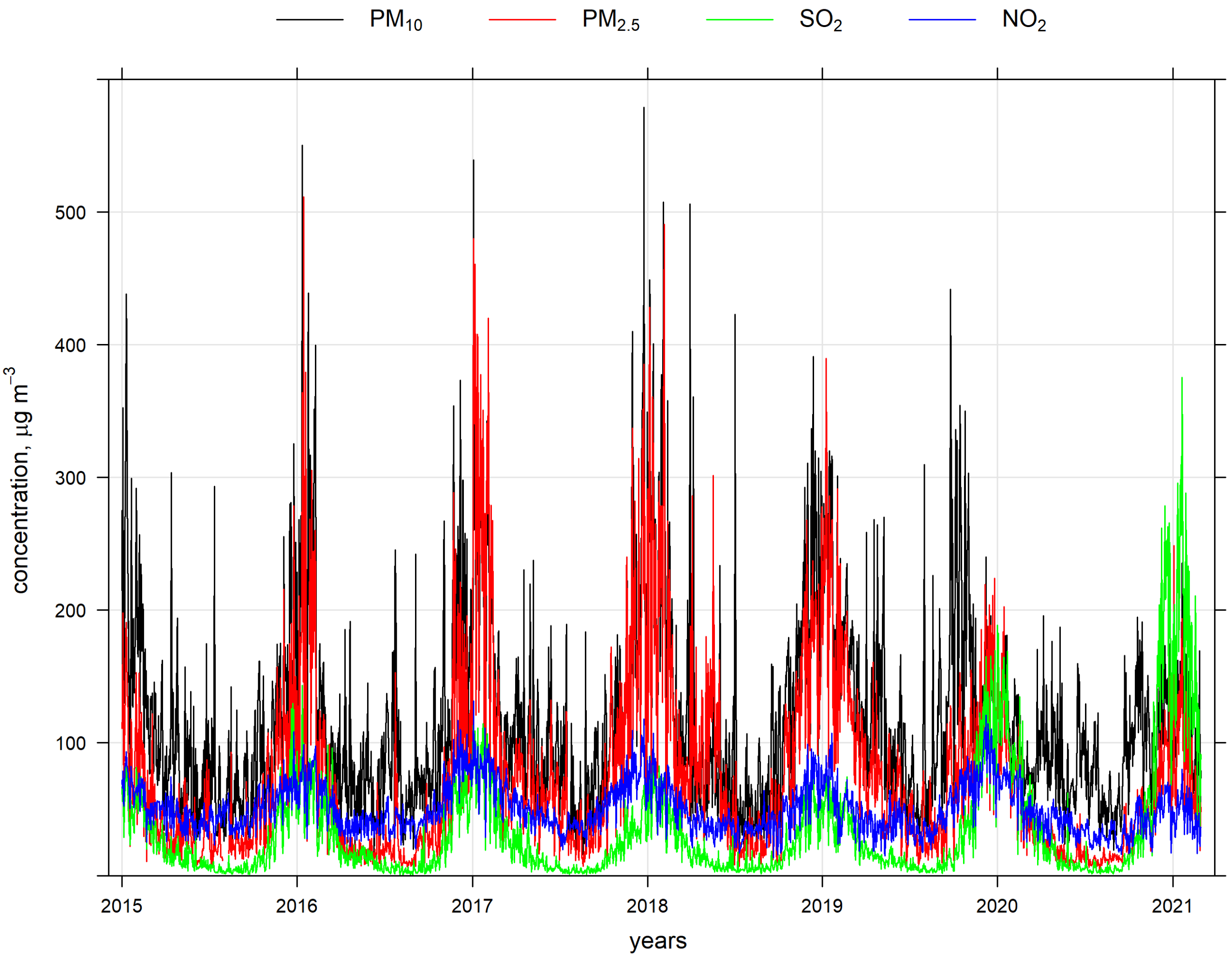


Fig. 2. Time series of daily mean NO_2, SO_2, PM_{10}, and $PM_{2.5}$ and concentrations from 1 January 2015 to 1 March 2021 averaged over the air quality monitoring sites in Ulaanbaatar.

It should be noted that even the concentrations are significantly reduced, the yearly-mean values of the pollutant concentrations remained persistently above the national standard values. Table 4 supplements Fig. 2 providing a number of days with average pollutant concentration from November 1 to February 28, which covers three sequential strict-lockdowns, exceeding one, two, and three times the national air quality standard levels.

From November-February in 2014–2020 to 2020–2021, the days with an average NO_2 concentration above the national air quality standard level reduced from 101 to 45. The strict-lockdowns during November 2020–February 2021 have resulted in a 55% reduction in the number of days exceeding the national air quality standard level of NO_2 compared to 2014-2020. During November 2020–February 2021, there were no days exceeding two and three times the national air quality standard level of NO_2. A similar feature is seen in many cities in the world (Acharya *et al.*, 2021). It is important to note that one of the substantial reasons for the decrease in NO_2 concentration was restrictions on city traffic during the strict-lockdown periods.

For winters 2019–2020 and 2020–2021, the number of days exceeding the national air quality standard level for PM_{10} decreased by 30%. For winters before 2019, the number of days with average PM_{10} concentrations exceeding three times the national air quality standard level ranged from 9 to 65, but for the past two winters, there were no such days.

For November 2017–February 2018, in 65 days the $PM_{2.5}$ concentration exceeded three times the national air quality standard level. For winters 2019–2020 and 2020–2021, the number of days exceeding the national air quality standard level for $PM_{2.5}$ decreased by 14% compared to 2014–2019. These sudden reductions of PM_{10} and $PM_{2.5}$ concentrations during the last two

Table 4. Days with average concentrations exceeding the national air quality standard levels of NO_2, SO_2, PM_{10}, and $PM_{2.5}$.

	Exceedance factor	Concentration (μg m^{-3})	Nov. 2014–Feb. 2015	Nov. 2015–Feb. 2016	Nov. 2016–Feb. 2017	Nov. 2017–Feb. 2018	Nov. 2018–Feb. 2019	Nov. 2019–Feb .2020	Nov. 2020–Feb. 2021
NO_2	1	≥ 50	84	101	112	108	91	109	45
	2	≥ 100	0	1	8	6	1	5	0
	3	≥ 150	0	0	0	0	0	0	0
SO_2	1	≥ 50	39	63	77	43	48	98	105
	2	≥ 100	0	5	10	0	0	56	87
	3	≥ 150	0	0	0	0	0	11	56
PM_{10}	1	≥ 100	115	93	103	116	116	81	73
	2	≥ 200	56	35	56	94	91	3	1
	3	≥ 300	14	12	9	65	46	0	0
$PM_{2.5}$	1	≥ 50	95	103	110	116	116	98	87
	2	≥ 100	42	65	84	94	91	42	30
	3	≥ 150	13	32	59	65	46	8	6

winters could be linked to the transition from raw coal to briquette fuel. However, a greater declining trend is exhibited in winter 2020–2021, when the sequential strict-lockdowns have been imposed due to the COVID-19 pandemic.

Before winter 2019–2020, there were no days with average SO_2 concentrations exceeding three times the national air quality standard level, but for the last two winters, the days exceeding three times the national air quality standard level significantly increased—no days versus 11 and 56 days in winter 2019–2020 and 2020–2021, respectively.

Descriptive statistics of each strict-lockdown period with respect to the same periods in the same periods in the previous five years are done. The mean and standard deviation of pollutant concentrations during the strict-lockdown periods and their changes from the same periods in the previous five years are shown in Table 5. All pollutants except SO_2 present declines for the period from November 2020 to February 2021. Notable declines are apparent during the strict-lockdown periods (L1, L2, and L3). During the strict-lockdown periods, lower concentrations (from 39% to 72%) were observed. The concentration levels are likely to go up once the situation back to normal (N1 and N2) but remain still lower compared to the same periods in the previous five years.

On average, a decrease of 41%, 53%, and 55% in NO_2, PM_{10}, and $PM_{2.5}$ concentrations, respectively, is found, whereas a 229% increase in SO_2 concentrations during the strict-lockdown periods compared to the same periods in the previous five years. Such effect of lockdown on the reduction of NO_2 was observed in other cities of the world (Fu *et al.*, 2020; Acharya *et al.*, 2021) as a result of decreases in various anthropogenic activities.

Visible reductions in PM_{10} and $PM_{2.5}$ remain to be consistently seen for the period from November 2020 to February 2021. The substantial reductions in PM_{10} and $PM_{2.5}$ concentrations from November 2020 to February 2021 compared to the previous five years could be due to the combination of fuel change and COVID-19 mitigation measures. The maximum decrease in NO_2, PM_{10}, and $PM_{2.5}$ concentrations was observed in L3. An opposite trend is observed for SO_2 concentration. SO_2 concentration increased from twofold (212%) to threefold (331%) during the periods. Time series of daily mean NO_2, SO_2, PM_{10}, and $PM_{2.5}$ concentrations from November to March are shown in Fig. 3. The figure reveals significant decreases in NO_2, PM_{10}, and $PM_{2.5}$ concentrations during the whole period covering three sequential strict-lockdowns.

The daily-mean (highest) NO_2 concentration reduction ranged from 27 (25) % to 41 (39) % between November 2020–March 2021 and the same periods in the previous five years. NO_2 concentration for the period between November 2020 and March 2021 decreased by 35% on average compared to the previous five years. During the three sequential strict-lockdowns, the daily NO_2 concentration drops to below 20 μg m^{-3} first ever since 2015.

To take a further look at the variations of pollutant concentrations between strict-lockdowns, we compare the pollutants concentrations averaged over seven days before and after the start of the strict-lockdown. The daily mean concentrations of NO_2 were 41.8, 63.6, and 53.6 μg m^{-3}

Table 5. Information of COVID-19 strict-lockdown periods in Ulaanbaatar and mean and standard deviation of NO_2, SO_2, PM_{10}, and $PM_{2.5}$ concentrations during and between the strict-lockdown periods.

	Period	Details	NO_2 ($\mu g\ m^{-3}$)		SO_2 ($\mu g\ m^{-3}$)		PM_{10} ($\mu g\ m^{-3}$)		$PM_{2.5}$ ($\mu g\ m^{-3}$)	
			Averaged for previous five years	2020–2021	Averaged for previous five years	2020–2021	Averaged for previous five years	2020–2021	Averaged for previous five years	2020–2021
L1	11 November–14 December	Public strict-lockdown after the first local case	71.8 ± 29.8	43.6 ± 12.2 (↓39%)	52.6 ± 34.2	112.0 ± 62.4 (↑212%)	167.9 ± 32.6	101.3 ± 29.9 (↓40%)	130.4 ± 27.7	59.3 ± 24.8 (↓55%)
N1	14 December–22 December	No strict-lockdown	81.8 ± 36.7	62.1 ± 6.6 (↓24%)	69.9 ± 49.3	231.7 ± 26.3 (↑331%)	198.1 ± 36.1	140.4 ± 15.6 (↓29%)	155.6 ± 46.2	99.7 ± 13.4 (↓36%)
L2	23 December 2020–10 January 2021	Second public strict-lockdown	73.9 ± 26.0	44.4 ± 13.7 (↓39%)	74.4 ± 44.4	164.9 ± 60.2 (↑222%)	202.3 ± 30.3	106.1 ± 34.2 (↓48%)	179.3 ± 31.9	88.9 ± 51.4 (↓50%)
N2	11 January–10 February	No strict-lockdown	70.2 ± 17.1	52.6 ± 12.5 (↓25%)	71.7 ± 23.3	209.6 ± 72.7 (↑292%)	212.5 ± 85.7	122.8 ± 40.9 (↓42%)	190.2 ± 85.4	102.4 ± 38.1 (↓46%)
L3	11–23 February 2021	Third public strict-lockdown	63.2 ± 24.0	34.4 ± 8.9 (↓45%)	51.5 ± 25.6	129.7 ± 41.6 (↑252%)	151.8 ± 30.2	43.1 ± 20.6 (↓72%)	125.3 ± 23.1	51.4 ± 16.2 (↓59%)

before the first, second, and third strict-lockdown periods, which reduced to 33.5, 47.5, and 35.3 $\mu g\ m^{-3}$, respectively. The NO_2 concentrations were reduced by 20%, 25%, and 34%, respectively.

The daily mean concentrations of SO_2 were 46.8, 233.6, and 167.5 $\mu g\ m^{-3}$ before the first, second, and third strict-lockdown periods, which reduced to 49.9, 156.9, and 139.5 $\mu g\ m^{-3}$, respectively. The SO_2 concentrations changed by –7%, 33%, and 17%, respectively.

The daily mean concentrations of PM_{10} were 118.6, 142.0, and 108.9 $\mu g\ m^{-3}$ before the first, second, and third strict-lockdown periods, which reduced to 87.6, 103.5, and 78.4 $\mu g\ m^{-3}$, respectively. The PM_{10} concentrations were reduced by 26–28%.

The daily mean concentrations of $PM_{2.5}$ were 45.9, 100.4, and 85.9 $\mu g\ m^{-3}$ before the first, second, and third strict-lockdown periods, which reduced to 34.9, 77.2, and 57.4 $\mu g\ m^{-3}$, respectively. The $PM_{2.5}$ concentrations are reduced by 24%, 23%, and 33%, respectively.

Among NO_2, PM_{10}, and $PM_{2.5}$, the NO_2 concentrations significantly reduced by 34% after the third strict-lockdown. The third strict-lockdown exhibited the greatest reductions in pollutant concentrations.

Fig. 4 shows that the probability distribution functions (PDFs) of concentrations of NO_2, PM_{10}, and $PM_{2.5}$ were consistently lower during the three sequential strict-lockdown periods.

The peak occurrence of NO_2, PM_{10}, and $PM_{2.5}$ concentrations during strict-lockdown periods are 45.3, 76.7, and 52.5 $\mu g\ m^{-3}$, while they were 70.3, 128.6, and 113.1 $\mu g\ m^{-3}$, respectively, during the same periods in the previous five years. The percentage exceeding the national standard (MNS 4585:2016) level for NO_2, PM_{10}, and $PM_{2.5}$ constituted 23%, 50%, and 67% during the lockdown periods while it was 89%, 84%, and 91%, respectively, during the same periods in previous five years. NO_2 experienced the greatest benefit, with a –66% reduction in percentage exceeding the national standard value.

For SO_2, high concentrations of SO_2 became more frequent during the strict-lockdown periods compared to the same periods in the previous five years. The percentage exceeding the national standard level for SO_2 increased from 54% to 89%. The peak occurrence of SO_2 concentration during

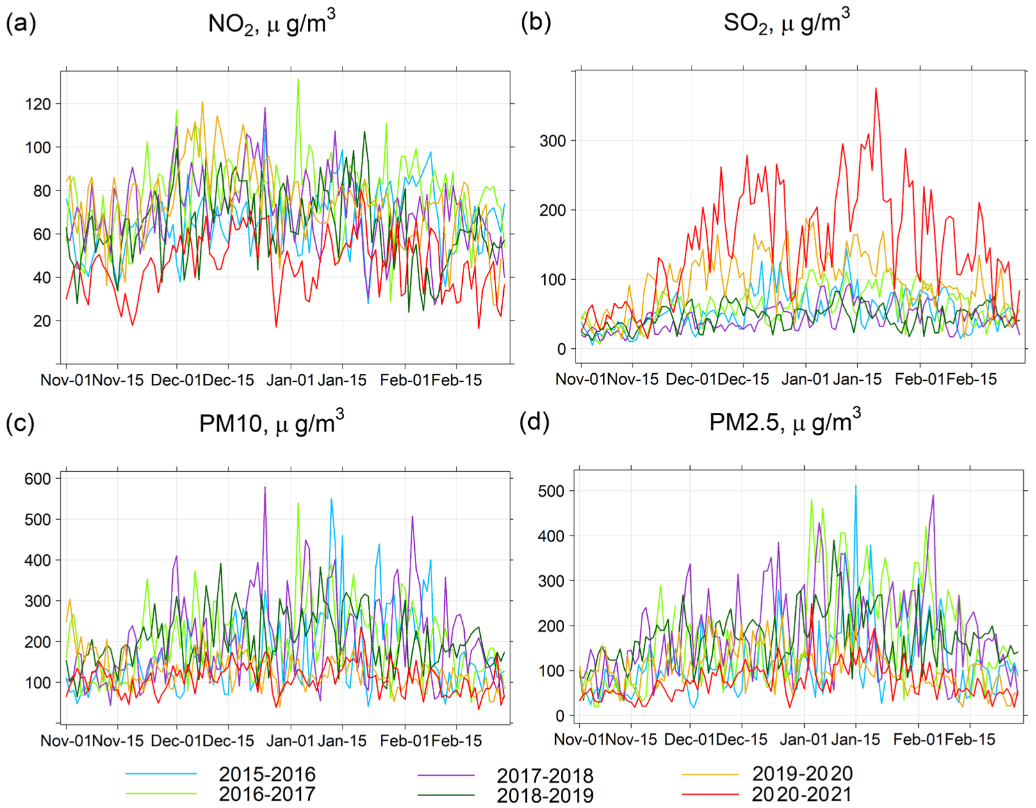


Fig. 3. Time series of NO_2, SO_2, PM_{10}, and $PM_{2.5}$ concentrations from 1 November to 28 February.

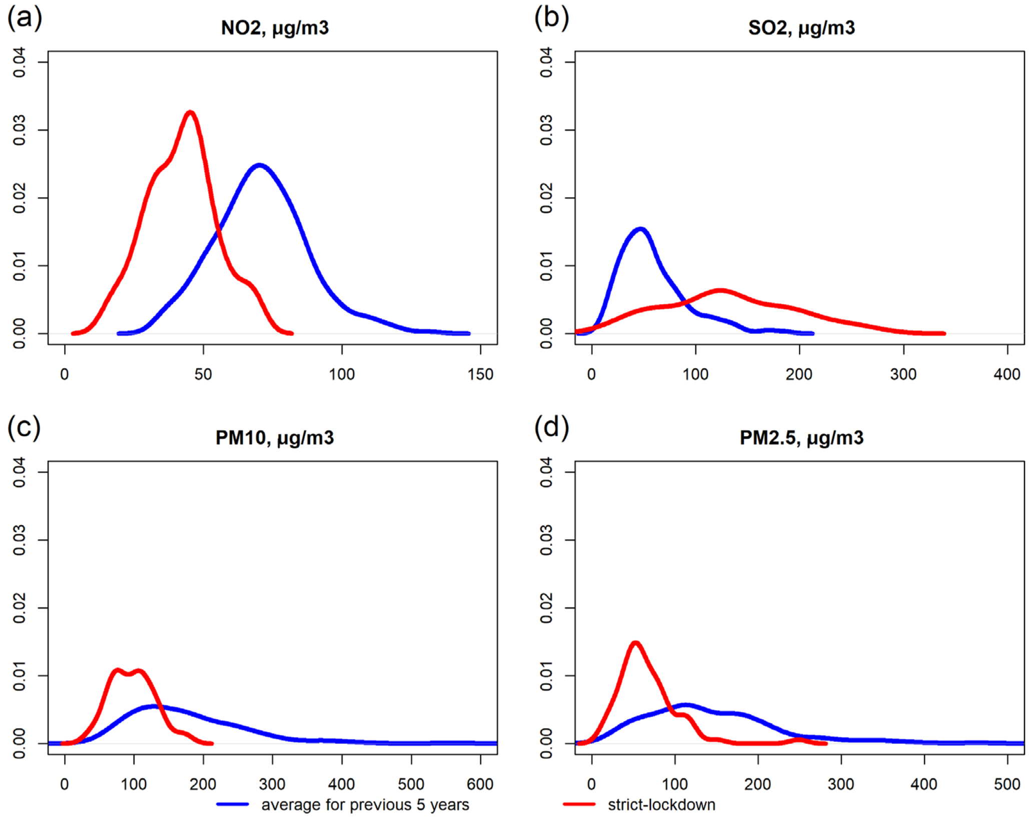


Fig. 4. Probability distribution functions of (a) NO_2, (b) SO_2, (c) PM_{10}, and (d) $PM_{2.5}$ concentrations for averaged over strict-lockdown periods (red) and the same periods in previous five years (blue).

strict-lockdown periods was 46.8 µg m^{-3}, while it is increased to 123.5 µg m^{-3} during the same periods in the previous five years.

The hourly patterns of the pollutant concentrations are illustrated in Fig. 5. The pollutant concentrations showed two peaks during the day.

The concentrations of NO_2, PM_{10}, and $PM_{2.5}$ are recorded as being substantially less during the strict-lockdown periods. For example, daily mean NO_2, PM_{10}, and $PM_{2.5}$ concentrations during strict-lockdowns were 63.3, 158.7, and 120.2 µg m^{-3}, which were reduced by 33, 39, and 46 %, respectively, when compared with those of the same periods in the previous five years. SO_2 concentration exhibited an increasing trend against previous years. The changes in concentrations were observed, however, the time of maximum and minimum concentrations are not changed much. These results clearly indicate that measures taken during the strict-lockdowns have substantially affected the air pollution in Ulaanbaatar.

As an extension of the measurement data to illustrate the spatial variations of NO_2 for the study period, tropospheric NO_2 columns from TROPOMI during COVID-19 strict-lockdown and no strict-lockdown periods (L1, N1, L2, N2, and L3) in winter 2020-2021 are shown in Fig. 6. The tropospheric NO_2 columns over the Ulaanbaatar are shown in Fig. 6(a) for the first COVID-19 strict-lockdown period from November 11, 2020 to December 14, 2020 (L1). Fig. 6(b) illustrates that the tropospheric NO_2 concentration has remained high (> 0.00021 mol m^{-2}) from December 14, 2020 to December 22, 2020 during no strict-lockdown (N1).

TROPOMI data for NO_2 at the city scale showed a reduction for lockdown periods as compared to non-lockdown periods. The observed reduction between N1 and L2 based on TROPOMI data was 48.6% for the whole city, as compared to an average reduction of 28.5% for the 11 monitoring stations equipped with NO_2 sensors. Between N2 and L3, a reduction of 35.2% was observed for

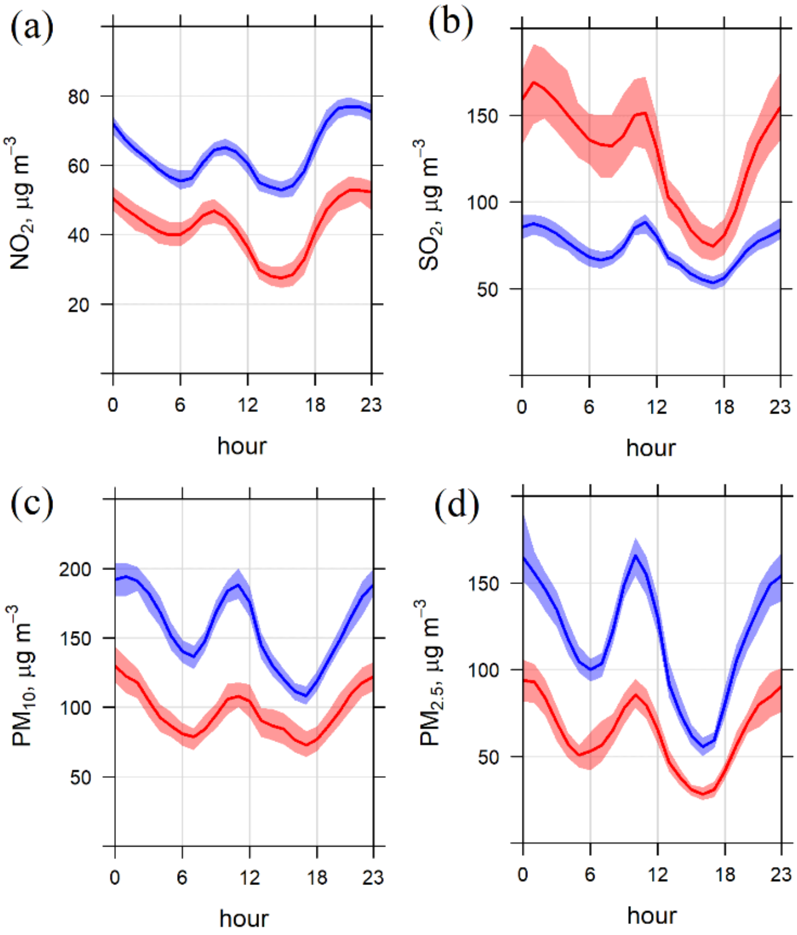
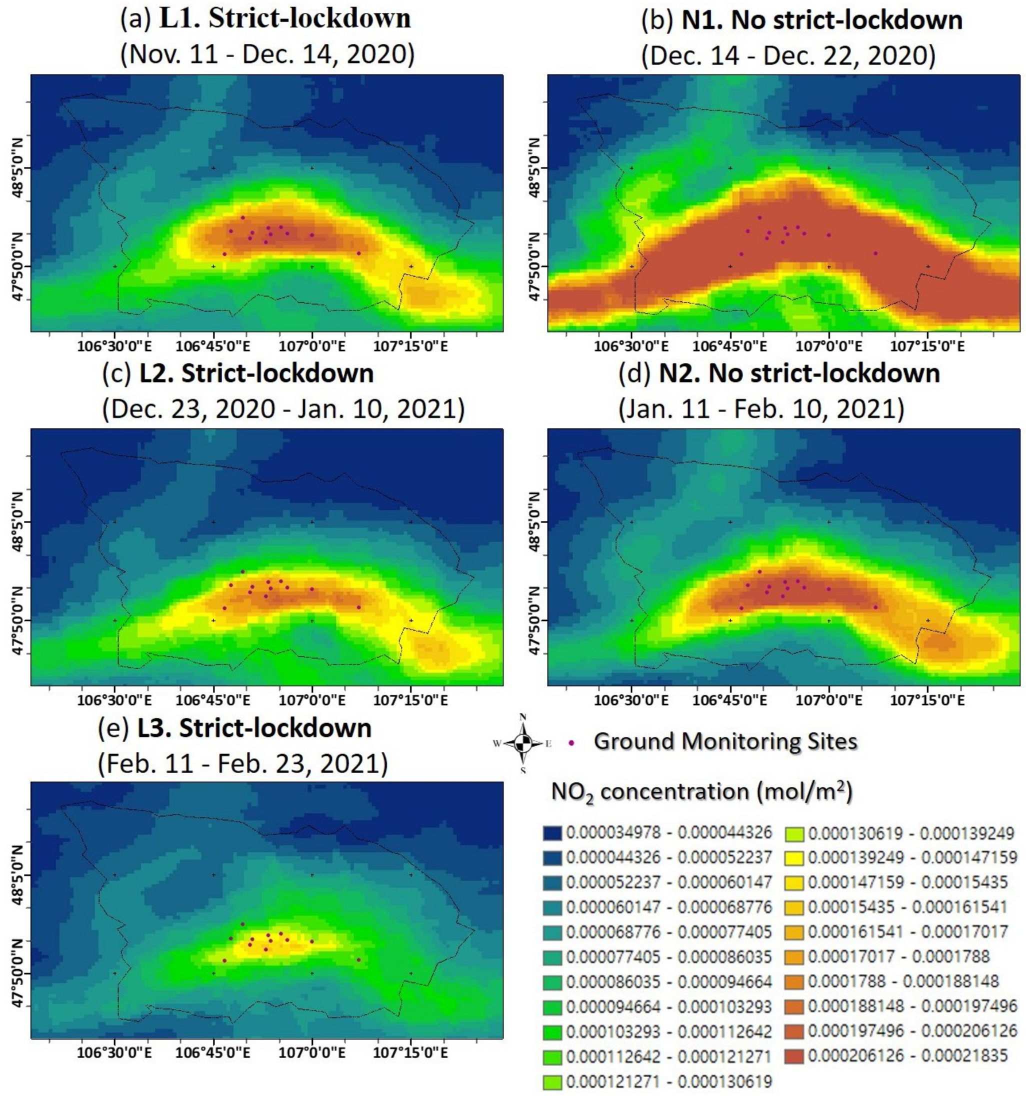


Fig. 5. Hourly variations in (a) NO_2, (b) SO_2, (c) PM_{10}, and (d) $PM_{2.5}$ concentrations averaged over strict-lockdown periods (blue) and the same periods in the previous five years (red).


(a) L1. Strict-lockdown (Nov. 11 - Dec. 14, 2020)

(b) N1. No strict-lockdown (Dec. 14 - Dec. 22, 2020)

(c) L2. Strict-lockdown (Dec. 23, 2020 - Jan. 10, 2021)

(d) N2. No strict-lockdown (Jan. 11 - Feb. 10, 2021)

(e) L3. Strict-lockdown (Feb. 11 - Feb. 23, 2021)

Fig. 6. Tropospheric NO_2 column densities over Ulaanbaatar observed by Sentinel-5P TROPOMI during the strict-lockdowns (left panel) and periods between them (right panel). Details of the abbreviations (L1, N1, L2, N2, and L3) are given in Table 5.

the city area based on TROPOMI data, as compared to an average reduction of 34.6% for the 11 monitoring stations. In this context, it should be mentioned that the monitoring stations were set up at locations that represent different pollution pattern (including sites with a high density of heating stoves and sites with significant traffic), but that averages may not be fully representative for the entire city. Moreover, one of the monitoring stations (Bayankhoshuu) was not equipped with an NO_2 sensor, thus leading to an information gap for ground-based data in one of the city's largest and most highly polluted ger areas. As standard deviations for NO_2 concentrations across the city were high for TROPOMI data (between ±30% and ±59% depending on the time period), averages were also calculated for 1 km buffer zones around the monitoring stations. In this case, standard deviations were far smaller (between ±8% and ±11%) for the time periods considered, and the observed reductions were 53.4% (between N1 and L2) and 35.7% (between N2 and L3). All in all, TROPOMI-based observations allowed a realistic assessment of general trends of NO_2 pollution (see Fig. 7) while also providing coverage of areas without monitoring stations.

Studies have proved these tropospheric NO_2 hotspots in downtown and midtown areas are associated with human activities including ground traffic and industrial activities (Hashim *et al.*, 2021; Huang *et al.*, 2021; Rissman *et al.*, 2013). Apparently, just after lockdown measurements were imposed from December 23, 2020 to January 10, 2021 (L2), the NO_2 concentrations dropped

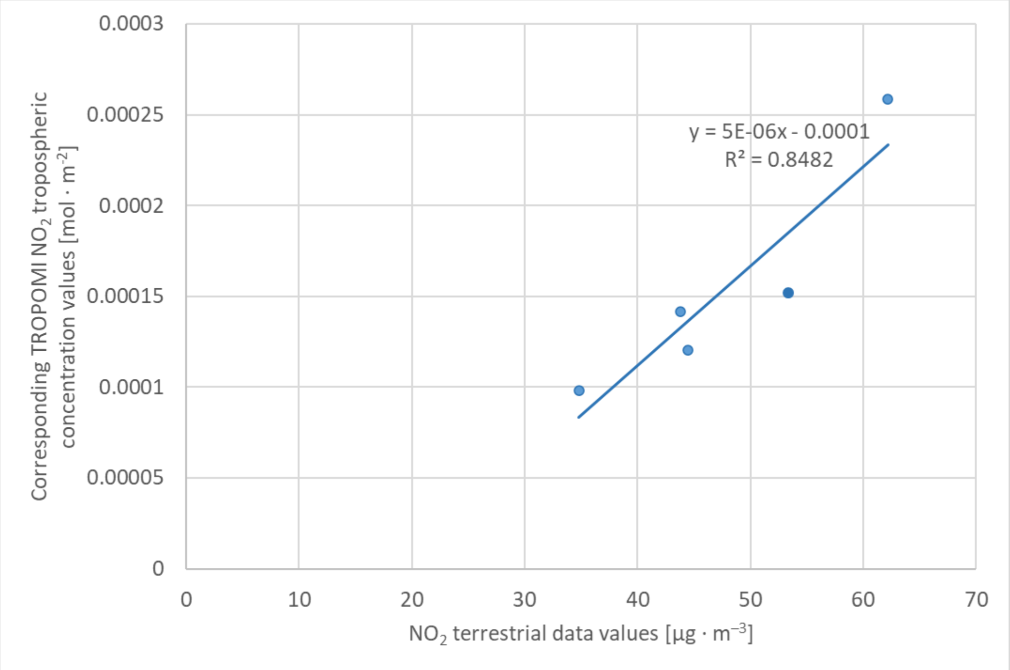


Fig. 7. The correlation analysis between terrestrial data and TROPOMI NO_2 tropospheric concentration.

sharply as shown in Fig. 6(c). However, during no strict-lockdown period from January 11, 2021 to February 10, 2021 (N2), NO_2 concentrations once again increased as exhibited in Fig. 6(d). Another significant reduction in NO_2 concentrations was observed during the third lockdown from February 11, 2021 to February 23, 2021 (L3) as documented in Fig. 6(e).

Previous studies have also shown a reduction of tropospheric NO_2 columns in 2020 lockdown period over various regions in the world (Goldberg *et al.*, 2020; Hashim *et al.*, 2021; Huang *et al.*, 2021; Wang *et al.*, 2021). Likewise, similar results have been reported in Asia regions, particularly Wang and Su (2020) and Bauwens *et al.* (2020) investigated a sharp decline in NO_2 concentrations over China and South Korea respectively based on Sentinel-5P data. Our results are comparable with these studies, indicating that the COVID-19 lockdown played an important role in the NO_2 reduction.

The results of correlation analysis between terrestrial data over the ground station and TROPOMI NO_2 tropospheric concentration from Sentinel-5P are shown in Fig. 7. The results show that the NO_2 concentration retrieved by TROPOMI is highly correlated with the surface monitoring concentration of NO_2 in Ulaanbaatar (correlation coefficient = 0.91, R^2 = 0.85).

4 SUMMARY

Following the novel COVID-19 (Coronavirus) case that was spread worldwide, prevention measures were implemented by the Government of Mongolia. The spread of COVID-19 disease to the community was first reported on 10 November 2020 in Mongolia. Starting 11 November 2020, the Government of Mongolia and the State Emergency Commission announced a series of intermittent strict-lockdowns to prevent the COVID-19 spread. This study focuses on three sequential strict-lockdowns from November 2020 to February 2021 which were announced to discontinue the novel coronavirus spread. A significant effect on air quality has been seen in Ulaanbaatar, Mongolia.

The impact of strict-lockdown on air pollution in Ulaanbaatar was assessed by comparing air pollutant concentrations before and during strict-lockdowns and during non-strict lockdown periods. Changes in Ulaanbaatar's air quality showed significant declines in NO_2 (up to 45%), PM_{10} (up to 72%), and $PM_{2.5}$ (up to 59%) concentrations between November 2020 and March 2021 compared to the previous five years. These reductions were among the greatest observed across

Asia, which is plausible considering the strict character of the lockdowns and the transition to cleaner coal briquettes. However, the concentrations were still above the national standard values, and SO_2 concentrations showed an increasing trend in the last two years, especially in winter. The reason could be attributed to the contents of the briquette fuel consumed in households in ger areas after the city-wide transfer from the raw coal to briquette fuel and the increased demand in consumption of briquette fuel in households due to long hours spent at home. The measures taken during the strict-lockdown periods clearly influenced the values of daily patterns of NO_2, PM_{10}, and $PM_{2.5}$ concentrations. The maximum concentration peaks appreciably decreased. In contrast, it is important to note that SO_2 concentration increased during the last two winter months after 2019. Furthermore, Sentinel-5P retrieved NO_2 tropospheric concentrations which were employed as an extension to illustrate changes of several pollutants during the COVID-19 strict and non-strict lockdown periods, are in agreement with the reductions observed at ground stations. Our current study underlines the findings of studies from other parts of the world, revealing both positive and negative impacts of lockdowns on air quality for Ulaanbaatar, Mongolia. However, as Ulaanbaatar has been developing very dynamically in recent years, and a major campaign to substitute the fuel for heating for about half of the city's households was implemented just prior to the pandemic, it is difficult to fully disentangle the impacts of COVID-19 from other developments. As only preliminary findings on the fuel substitution exist so far, the related uncertainties need to be addressed once the pandemic situation has improved and consolidated findings on the impacts of fuel substitution become possible.

ACKNOWLEDGEMENTS

Daniel Karthe would like to express his gratitude to German Academic Exchange Service (DAAD) for funding a long-term lectureship at the German-Mongolian Institute for Resources and Technology (GMIT).

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