Effect of COVID-19 Lockdown on Air Quality: Evidence from South Asian Megacities

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ABSTRACT

Anthropogenic activities were greatly restricted in many South Asian cities during the COVID-19 (Coronavirus disease-2019) pandemic creating an opportunity to observe source reduction of air pollutants. This study analyzed the change in columnar nitrogen dioxide (NO_2) and particulate matter ($PM_{2.5}$, aerodynamic diameter $\leq$2.5 µm) in five megacities of South Asian countries (Delhi, Dhaka, Kathmandu, Kolkata, and Lahore) from April 1 - May 31 over the previous three years (2018-2020). The Dutch-Finnish Ozone Monitoring Instrument (OMI) provided satellite-based daily tropospheric columnar NO_2 values for this study. Ground-based hourly $PM_{2.5}$ data were collected from the World's Air Pollution: Real-time Air Quality Index Project. The study observed a decrease of tropospheric columnar NO_2 in selected cities in 2020 compared to 2018 and 2019 from April 1 - May 31. The mean daily reading of $PM_{2.5}$ was 36.56% and 45.44% less in Delhi; 12.67% and 23.46% less in Dhaka; in Kathmandu 28.32% and 37.42% less; in Kolkata 41.02% less in 2020 than 2018 and 34.08% less in 2019 during April 1 - May 31. The $PM_{2.5}$ was 44.26% less in 2020 than in 2019 during April 9 - May 31 in Lahore. The daily mean difference in concentration during April 1 - May 31, 2018-2020 was significantly lower at α=0.01 level for both pollutants. Introducing appropriate mitigation measures would provide safer environments and reduce future air pollution in South Asian cities.

1. INTRODUCTION

1.1 Coronavirus disease (COVID-19) pandemic

The world was reminded of environmental determinism in December 2019 by a new strain of Coronavirus (COVID-19). The virus appeared to have originated in Wuhan, China (Chen et al., 2020). This respiratory illness spread worldwide and led to a global pandemic. COVID-19 pandemic has impacted many aspects of human life and the global economy. A reduction of pollution has occurred due to limited social and economic activities despite the negative impacts of COVID-19 in many aspects of daily life (Dutheil et al., 2020). Most countries have tried to contain the spread of the highly contagious virus with massive COVID-19 screening tests, social distancing public policies, travel restrictions, and lockdown. The South Asian countries of Bangladesh, India, Nepal, and Pakistan restricted movements from the mid of March 2020 to mitigate the COVID-19 pandemic (Shrestha et al., 2020; Mahato et al., 2020; Nayeem et al., 2020).

The Bangladesh government reported the first three known cases on March 8, 2020 (IEDCR, 2020). To protect the population from this outbreak, the government declared a countrywide lockdown from March 23 to May 30, 2020 (Nayeem et al., 2020). Heavy vehicles (long road trucks) and diesel buses were restricted during the daytime in Dhaka during these weeks.

India identified the first case of COVID-19 on January 30, 2020; by July 7, 2020, India had the third-highest number of confirmed cases after the United States and Brazil (Kulkarni, 2020). The Indian government imposed a nationwide lockdown on

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March 24, 2020, for 21 days to control this outbreak extending it to May 31, 2020. The government restricted vehicle movements (except emergency services) in Delhi and Kolkata to comply with the social distancing policy.

Nepal reported the first COVID-19 positive patient on January 23, 2020, when a 31-year-old student returned to Kathmandu from Wuhan, China. In response, the Nepal government suspended on-arrival tourist visas for all countries from March 14 - April 30, 2020. After that, a countrywide lockdown came into effect on March 24, 2020, which ended on July 21, 2020 (Pradhan, 2020). The government also closed the land border entry points for third-country nationals and canceled all mountain climbing expeditions, including Mount Everest. Enforcement of these restrictions was from March 14 - April 30, 2020 (Himalayan Times, 2020).

Pakistan reported the first confirmed case on February 26, 2020. As a result, the Pakistan government closed shopping malls, markets, parks, and public gathering places. The government declared a 14-day lockdown from March 24 - April 6, later extended to April 30 (Sipra et al., 2020). The government shut down all land borders and canceled international and domestic flights.

With all these restraints in these four countries, only emergency services such as medical, healthcare, logistics, food supply chain, power sector, and banking were allowed to be carried on in a limited way. Therefore, less vehicle movement on the roads, restricted construction, and industrial activities has led to an emission reduction of various gases and particulate matter in the atmosphere (Nadzir et al., 2020).

1.2 Sources apportionment of air pollution over different cities

A study carried out in Delhi during the winter of 2013-2014, and the summer of 2014 identified the source apportionment of $PM_{2.5}$ as road dust (38%), vehicular pollution (20%), domestic sources (12%), industrial sources (11%), concrete batching (6%), and 13% from other sources (Nagar et al., 2017). Vehicular emission (51.4%), followed by industrial sources (24.5%) and road dust (21.1%) were identified as the significant sources of air pollution in Kolkata (Haque and Singh, 2017). In Dhaka, previous studies have identified brick kilns located near the city, uncontrolled open burning of trash, and vehicle exhaust as significant sources of $PM_{2.5}$ (Nayeem et al., 2020). Primary sources of $PM_{2.5}$ in Lahore are diesel emission and two-stroke vehicles (36%), biomass burning (15%), coal combustion (13%), and industrial activities (Dutkiewicz et al., 2009; Raja et al., 2010; Stone et al., 2010). Brick kilns (40%), motor vehicles (37%) biomass/garbage burning (22%), and soil dust (1%) have been identified as contributing sources in the Kathmandu Valley (Kim et al., 2015).

1.3 COVID-19 and air pollution

One of the significant environmental problems of developing countries is air pollution, mostly seen in urban areas due to exhaust from vehicles, brick kilns, industrial and construction activities, unsustainable farming, open waste dumping, and combustion of fossil fuels (Majumder et al., 2020; Nayeem et al., 2019; Razib et al., 2020; Nadzir et al., 2020; Hossain et al., 2019). These emissions are responsible for the release of several gaseous compounds such as carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), sulfur dioxide (SO_2), and particulate matter (coarse and fine particles) into the atmosphere. Among these compounds, the concentrations of nitrogen dioxide (NO_2) and fine particulate matter ($PM_{2.5}$) are monitored continuously in urban areas since these compounds have adverse impacts on human health (Latif et al., 2012; Banan et al., 2012; Nadzir et al., 2018). Increased levels of these pollutants may cause acute and chronic diseases resulting in 5.5 million unnecessary deaths annually (WHO, 2016).

Many satellite and ground-based air pollution studies have addressed the impacts of COVID-19 pandemic. A study reported that three cities in central China (Wuhan, Jingmen, and Enshi) had recorded total reductions of air pollutants of $PM_{2.5}$ by 30.1% and of NO_2 by 61.4% during the pandemic (Xu et al., 2020). The average air quality index (AQI) for these three cities decreased significantly compared to 2017-2019. In another study, the Copernicus Atmosphere Monitoring Service (CAMS) was used to observe the concentration of particulate matter ($PM_{2.5}$) in China and found a 20-30% reduction throughout lockdown compared to the previous three years of 2017, 2018, and 2019 during the same months (Zambrano et al., 2020). In one study over the peninsular Malaysia region, the concentration of $PM_{2.5}$ was found to be reduced by 58.4% during the lockdown (Abdullah et al., 2020). A study in Barcelona, Spain, using Copernicus Tropospheric Monitoring Instrument, reported a 51.0% reduction of tropospheric columnar NO_2 during the lockdown than the month before the lockdown (Tobías et al., 2020). A sharp declining trend of NO_2 concentrations was also observed in developed countries such as France, Germany, Italy, and Spain (ESA, 2020).

According to the 2019 IQAir report, Bangladesh (1st), Pakistan (2nd), India (5th), and Nepal (8th) are some of the world's most polluted countries for $PM_{2.5}$ exposure with high urban growth rates (UNCTAD, 2020), Delhi topped the list of the world's most polluted capital cities followed by Dhaka (IQAir, 2019). Since India ranks as the second-most populous country, Kolkata, a very crowded city just adjacent to Bangladesh surrounded by numerous coal power plants, is also worthy of being evaluated (Vadrevu et al., 2020). While Islamabad, the capital city of Pakistan, ranked 14th, $PM_{2.5}$ exposure data is not available. This study considered, a relative nearby alternative Lahore (270 km), where a strict lockdown was imposed and is a significant polluted city according to the US Air Quality Index (Sipra et al., 2020). In Nepal, Kathmandu has the 6th highest $PM_{2.5}$ value of any capital being analyzed (IQAir, 2019). As several studies found that atmospheric pollution is a transboundary issue (Shehzad et al., 2020; Rana et al., 2016), only the research on a regional scale can identify issues. According to the Koppen climate classification scheme, part of Delhi and Lahore are considered Bsh (semi-arid), other parts of Delhi and Kathmandu are in a Cwa (humid subtropical) climatic zone, and Kolkata and Dhaka fall in a Aw (tropical wet-and-dry) zone (Lohmann et al., 1993) and these cities are also part of the regional wind system. This study chose these five megacities of four neighboring countries since they are cities in member countries of the regional forum SAARC (South Asian Association of Regional Cooperation). We have carried out this study to observe the impacts of COVID-19 lockdown on air quality in those five polluted megacities of South Asia. The objective of this study was to analyze the variations in satellite-derived tropospheric columnar NO_2 and ground-based $PM_{2.5}$ concentration in selected South Asian megacities: Delhi, Dhaka, Kathmandu, Kolkata, and Lahore for the three years (2018-2020) at the same period of April 1 - May 31.

2. METHODOLOGY

2.1 Tropospheric NO_2 Vertical Column Densities (VCDs)

The Dutch-Finnish Ozone Monitoring Instrument (OMI), a UV-Visible wavelength spectrometer on the polar-orbiting NASA Aura satellite (https://so2.gsfc.nasa.gov/no2/no2_index.html), provided daily tropospheric columnar NO_2 values. This OMI sensor measures direct and atmospheric backscattered sunlight in the ultraviolet-visible (UV-Vis) zone ranging from 270 to 500 nm (Levelt et al., 2006). The normal spatial resolution is 24 × 13 km^2 in nadir and was zoomed into 13 × 13 km^2 to monitor urban scale pollution sources (Boersma et al., 2004). In this study, level 2 data were collected as comma-separated value (CSV) files to detect tropospheric columnar NO_2 in five megacities of South Asian countries during the COVID-19 pandemic compared to 2018 and 2019 during the same months (April-May). The 1 × 1 degree grid boxes surrounding each city was calculated to be: Delhi (76.709N 28.1139E 77.709N 29.1139E); Dhaka (89.9201N 23.308E 90.9201N 24.308E); Kathmandu (84.824N 27.2172E 85.824N 28.2172E); Kolkata (87.9001N 22.0667E 88.9001N 23.0667E), and Lahore (73.8436N 31.0497E 74.8436N 32.0497E). We retrieved average spatial maps of tropospheric columnar NO_2 in the troposphere with 0.25° × 0.25° resolution from the GIOVANNI online platform (GIOVANNI, 2020).

2.2 Ground level $PM_{2.5}$

$PM_{2.5}$ data were gathered from April 1 - May 31 over the last three years (2018-2020) from four selected Southeast Asian cities: Dhaka, Kolkata, Delhi, and Kathmandu. Data from April 9 - April 30, 2019, and May 9 - May 31, 2020 were used for Lahore since other data was lacking (Figure 1). We obtained hourly readings of $PM_{2.5}$ from the publicly available air quality data at World's Air Pollution: Real-time Air Quality Index Project (Air Now, 2020). Ground-based $PM_{2.5}$ monitoring stations, located at or near the US embassies and consulates of each country, record data. Several researchers have used this data source to determine compliance with air quality standards, simulate model, forecast air quality, study epidemiology, and assess health risk (Diao et al., 2019; Bulto, 2020; Yousefian et al., 2020; Roy et al., 2020). In the global village, using open-access air quality data helps develop integrated actions to control air pollution.

2.3 Data analysis

SPSSv20 and Microsoft Excelv10 were used for data processing, analysis, and preparing tables and graphs. Tukey's post hoc multiple comparison test was conducted to determine the significant level of changes

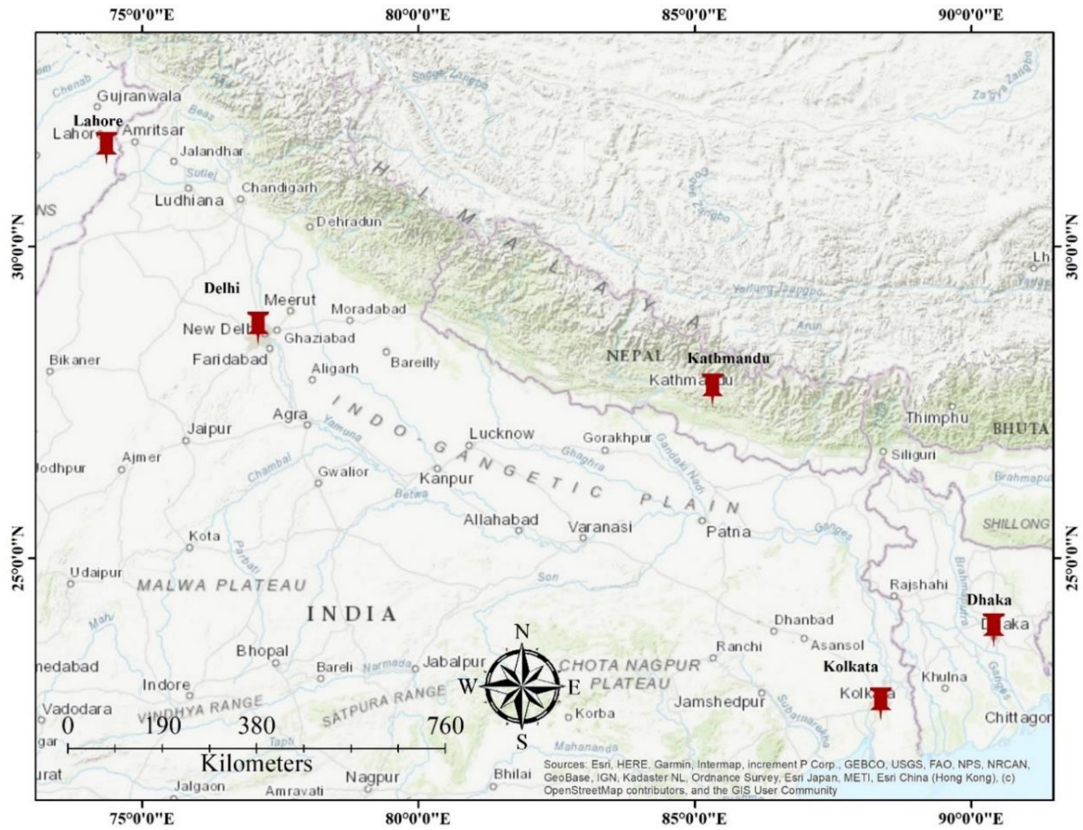


Figure 1. Geographical distribution of the selected cities in South Asian countries

in the selected years for both $PM_{2.5}$ concentration and tropospheric columnar NO_2. ArcGIS 10.2.1 was used to visualize the study area map.

3. RESULTS AND DISCUSSION

3.1 Tropospheric NO_2 Vertical Column Densities (VCDs) measured by OMI

The tropospheric columnar NO_2 observed from space through OMI denote emissions of nitrogen oxides ($NOx = NO + NO_2$) formed from fossil fuel combustion in industries, biomass burning, fires, and lightning. The wind direction and speed transport the NO_2 away from its sources. Many of these anthropogenic pollution sources were inactive since Bangladesh, India, Nepal, and Pakistan implemented strict traffic restrictions and self-quarantine measures to control the expansion of the COVID-19 pandemic (Shrestha et al., 2020). Significant air pollution changes in Delhi, Dhaka, Kathmandu, Kolkata, and Lahore resulted. This study observed a decreasing trend of tropospheric columnar NO_2 compared to previous years during the same months in these selected cities of South Asia (Figure 2). Tropospheric columnar NO_2 values were much higher in 2018 in Delhi, Dhaka, Kolkata, and Lahore. In Kathmandu, the highest value observed was in 2019. Table 1 shows the daily average of tropospheric columnar NO_2 in the selected cities from 2018-2020 during April and May. Delhi observed a dramatic reduction in the daily tropospheric columnar NO_2 during the COVID-19 period of 48% and 45.6% compared to 2018 and 2019. In Dhaka, the daily average tropospheric columnar NO_2 was 4.36, 3.47, and 2.57 molecules/cm^2 in 2018, 2019, and 2020, respectively. The tropospheric columnar NO_2 values in 2020 were 41.0% and 25.9% lower relative to 2018 and 2019 during the lockdown. The rate was reduced in Kolkata by 24.7% and 17.6% in 2020 compared to the previous two years.

In Lahore, the daily average tropospheric columnar NO_2 concentration was 36.0% and 25.0% lower in 2020 during the COVID-19 period compared to 2018 and 2019. In Kathmandu, the 2020 tropospheric columnar NO_2 is 8.7% lower than in 2018 and 15.0% than in 2019. Other studies showed that Delhi had a significant tropospheric columnar NO_2 reduction during the lockdown period (Vadrevu et al., 2020; Shehzad et al., 2020). Kolkata, as a coastal city, saw less reduction (Vadrevu et al., 2020). Additionally, in Kolkata, most coal power plants were not closed during the pandemic, which may have contributed to less reduction (Vadrevu et al., 2020).

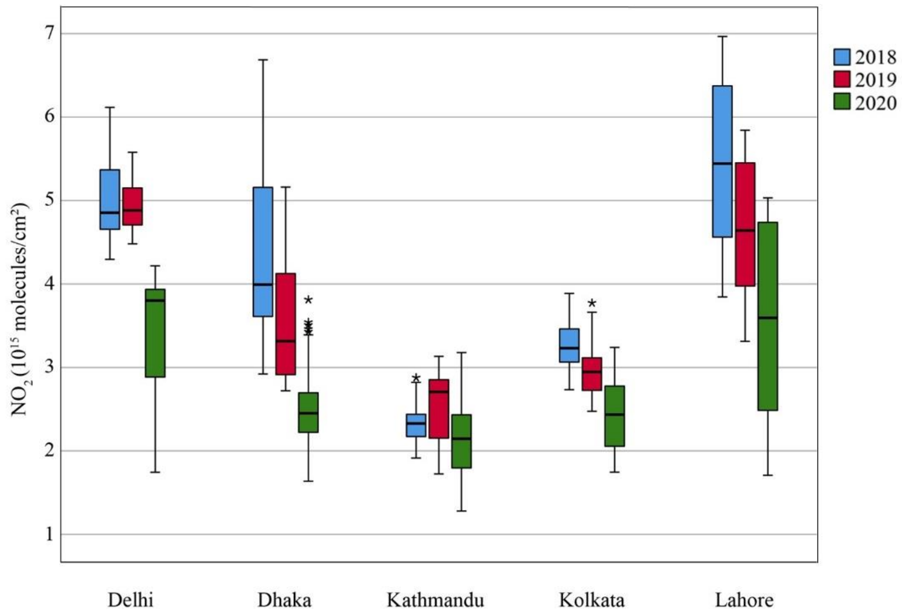


Figure 2. The whisker box plot shows the daily average of OMI derived tropospheric columnar NO_2 (10^{15} molecules/cm^2). A horizontal black line within the box marks the median; the lower boundary of the box indicates the 25th percentile, the upper boundary of the box indicates the 75th percentile. The whisker represents the maximum (upper whisker) and minimum value (lower whisker). Points above the whiskers indicate outliers.

Table 1. Daily Mean of Tropospheric Columnar NO_2 (10^{15} molecules/cm^2) with Relative Changes (%)

Location	Month	2018	2019	2020	A	B
Delhi	April	4.73	4.96	2.86	-65.5	-73.3
	May	5.32	4.94	3.92	-35.7	-26.0
	Average	5.03	4.95	3.40	-48.0	-45.6
Dhaka	April	5.06	4.03	2.67	-47.2	-33.7
	May	3.69	2.93	2.40	-34.8	-18.1
	Average	4.36	3.47	2.53	-41.0	-25.9
Kathmandu	April	2.48	2.26	2.20	-11.3	-2.5
	May	2.18	2.83	2.05	-6.1	-27.5
	Average	2.33	2.55	2.13	-8.7	-15.0
Kolkata	April	3.36	3.16	2.74	-18.4	-13.4
	May	3.15	2.78	2.17	-31.0	-21.9
	Average	3.25	2.97	2.45	-24.7	-17.6
Lahore	April	4.49	4.03	2.49	-44.4	-38.1
	May	6.36	5.22	4.60	-27.6	-11.9
	Average	5.44	4.64	3.57	-36.0	-25.0

Note: A=2020 vs 2018; B=2020 vs 2019

The reduction in Kathmandu may have occurred because of wildfires in the first half of April, open garbage burning, and cross border pollution haze (Nepal Times, 2020). Thermal inversions trap pollutants during the winter season, making conditions worse in this valley (Mahapatra et al., 2019).

Atmospheric NO_2 concentration has decreased in some developed countries during the COVID-19 outbreak. The readings from the Copernicus Sentinel-5P satellite showed a significant decrease of tropospheric columnar NO_2 concentrations during lockdown over Rome, Madrid, and Paris (Zambrano et al., 2020). The most substantial reduction of NO_2 was estimated at 51% in Barcelona (Tobías et al., 2020). Dhaka, Bangalore, Beijing, Bangkok, Delhi, and Nanjing experienced lower tropospheric columnar NO_2. Several major trade centers such as New York, London, Paris, Seoul, Sydney, and Tokyo experienced reduced atmospheric NO_2 levels (Roy et al., 2020, Shrestha et al., 2020). The Tukey post hoc test, as shown in Table 2, displays the significant changes in the daily tropospheric columnar NO_2 data in 2020. The mean differences are significantly lower (at α=0.01 level) in 2020 compared to 2018 and 2019 for the same period for all selected cities. Major cities of all selected countries are shown in Figure 3 comparing satellite measurements of background tropospheric columnar NO_2, supplied by OMI in 2018-2020. Analyses show that the tropospheric columnar NO_2 concentration reduced significantly during the lockdown. Combustion processes such as diesel and gasoline combustion from road traffic, manufacturing, power generation, and shipping industry release urban NO_2 (Tobías et al., 2020); most of these sectors ceased or reduced operations during the lockdown. In India, the average concentrations of tropospheric columnar NO_2 decreased by 45.99% in industrial areas and 50.61% in traffic-dominated locations (Mahato et al., 2020).

Table 2. Summary of Tukey's post hoc multiple comparisons between tropospheric columnar NO_2 and years

Location	(I) Year	(J) Year	Mean difference (I-J)	Std. Error
Delhi	2020	2018	-1.63[a]	0.09
		2019	-1.55[a]	0.09
Dhaka	2020	2018	-1.83[a]	0.14
		2019	-0.94[a]	0.14
Kathmandu	2020	2018	-0.21[b]	0.07
		2019	-0.43[a]	0.07
Kolkata	2020	2018	-0.80[a]	0.06
		2019	-0.52[a]	0.06
Lahore	2020	2018	-1.81[a]	0.18
		2019	-1.07[a]	0.18

[a] The mean difference is significant at α=0.001
[b] The mean difference is significant at α=0.01

3.2 Concentration of $PM_{2.5}$

Vehicle emissions, biomass burning, brick kilns, and construction activities generate $PM_{2.5}$, defined as fine particulate matter less than 2.5 microns. Many of these emission sectors were shut down worldwide during the COVID-19 induced lockdown. The whisker box plots in Figure 4 shows that Delhi, Dhaka, and Kathmandu had higher pollution levels in 2019 compared to 2018, showing the decreasing trend of $PM_{2.5}$ during the lockdown in five megacities of South Asia. During lockdown in 2020, the pollution level decreased noticeably in all the selected cities compared to the previous two years.

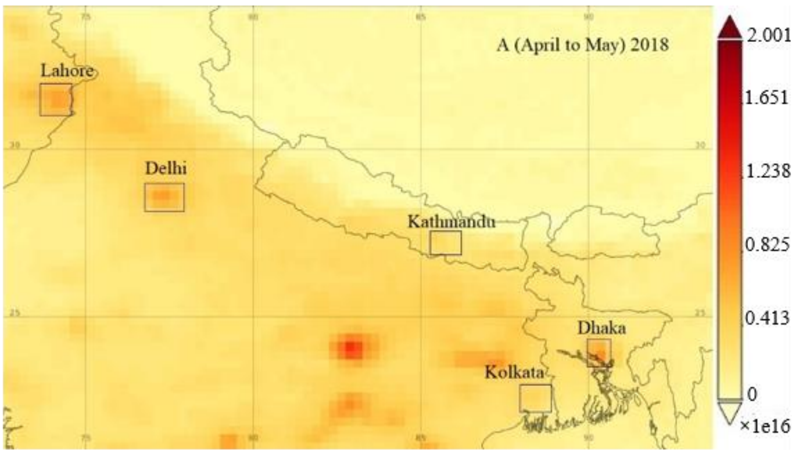
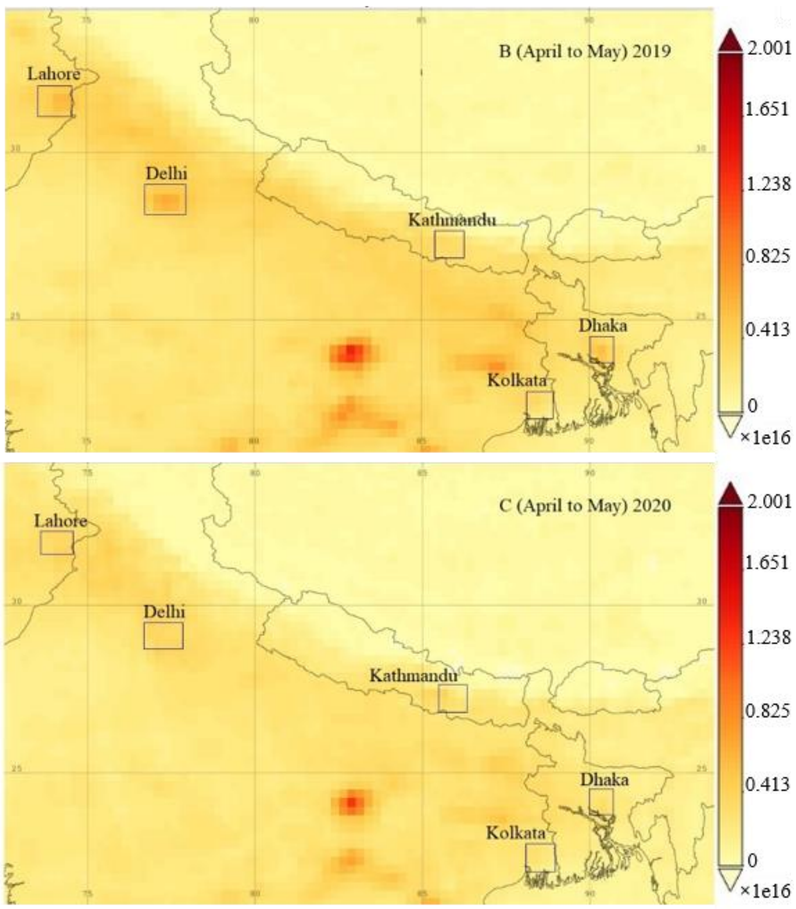


Figure 3. Spatial distribution of tropospheric columnar NO_2 in Delhi (76.709N, 28.1139E, 77.709 N, 29.1139E); Dhaka (89.9201N 23.308E 90.9201N 24.308E); Kathmandu (84.824N 27.2172E 85.824N 28.2172E); Kolkata (87.9001N 22.0667E 88.9001N 23.0667E) and Lahore (73.8436N 31.0497E 74.8436N 32.0497E) from 2018-2020 (Average of April-May)



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The daily mean of $PM_{2.5}$ concentration in five cities from 2018-2020 is in Table 3. Delhi's air contained 72.02, 83.74, and 45.69 µg/m^3 of $PM_{2.5}$ in 2018, 2019, and 2020 from April 1 - May 31. $PM_{2.5}$ concentration decreased during the COVID-19 period in 2020 in Delhi, reducing 36.6% compared to 2018 and 45.4% compared to 2019. Nagar et al. (2017) found the $PM_{2.5}$ levels in Delhi resulted from a regional problem caused by contiguous urban agglomerations.

In Dhaka, the mean concentration was 56.91 µg/m^3 in 2018, 64.93 µg/m^3 in 2019, and 49.70 µg/m^3 in 2020 from April 1 - May 31. The $PM_{2.5}$ concentration reduced by 12.7% compared to 2018 and 23.5% compared to 2019 during the lockdown in those months. Dhaka experienced less $PM_{2.5}$ reduction than other cities because construction of the Mass Rapid Transit (MRT) continued during COVID-19 lockdown (Nayeem et al., 2020). Other factors may have been meteorological characteristics (Mofijur et al., 2020), higher population density, greater dependence on fossil fuel for cooking, and reopening of industry. Market and shopping malls were open, allowing private vehicle movement inside the city (Nayeem et al., 2020).

In Kolkata, the daily concentration of $PM_{2.5}$ in 2020 decreased by 41.0% compared to 2018 and 34.1% relative to 2019. The $PM_{2.5}$ in Kathmandu was 28.3% less in 2020 than in 2018 and 37.4% less than in 2019. The Kathmandu valley geography causes large diurnal variability in temperature and relative humidity resulting in a corresponding gas-aerosol phase partitioning of NH_3, HNO_3, and HCl and aerosol solution affecting the pH (Islam et al., 2020).

In Lahore, only a comparison with the concentration of 2019 was available. $PM_{2.5}$ decreased by 44.26% in 2020 compared to 2019, more than in other cities. The $PM_{2.5}$ reduction in Delhi and Kolkata was more than in other cities during the lockdown. The restriction in social contact, the closing of restaurants, shops, and many commercial and administrative centers, reduced these air pollutants.

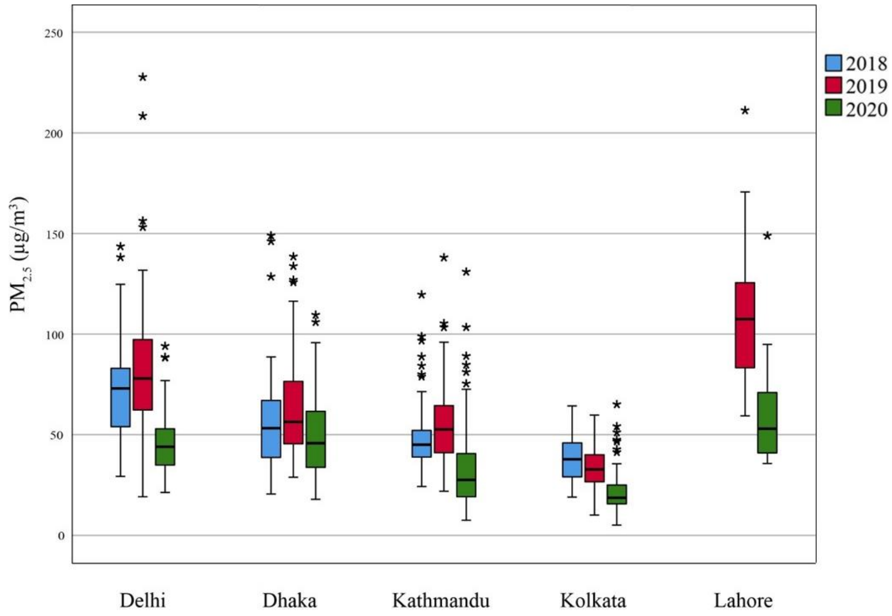

Figure 4. The whisker box plot shows the daily average of ground-level $PM_{2.5}$ (µg/m^3) concentration. A horizontal black line marks the median. The lower boundary of the box indicates the 25th percentile. The upper boundary of the box indicates the 75th percentile. The whisker represents the maximum (upper whisker) and minimum value (lower whisker). Points above the whiskers indicate outliers.

Table 3. Daily mean of $PM_{2.5}$ (µg/m^3) with relative changes (%)

Location	Month	2018	2019	2020	A	B
Delhi	April	71.47	75.13	40.72	-43.03	-45.80
	May	72.56	92.06	50.51	-30.39	-45.13
	Average	72.02	83.74	45.69	-36.56	-45.44
Dhaka	April	70.71	70.82	52.24	-26.12	-26.24
	May	43.55	59.04	46.52	-6.82	-21.21
	Average	56.91	64.93	49.70	-12.67	-23.46
Kathmandu	April	58.84	50.46	47.08	-19.99	-6.70
	May	40.13	62.34	24.02	-40.14	-61.47
	Average	49.33	56.50	35.36	-28.32	-37.42
Kolkata	April	41.60	34.37	28.06	-32.55	-18.36
	May	33.73	33.04	16.56	-50.90	-49.88
	Average	37.66	33.69	22.21	-41.02	-34.08
Lahore	May	DNA	109.14	60.84	DNA	-44.26
	Average	DNA	109.14	60.84	DNA	-44.26

Note: A=2020 vs 2018; B=2020 vs 2019; DNA=Data Not Available

Table 4 shows Tukey's post hoc analysis to test the significant changes in the daily average of $PM_{2.5}$ data based on 2020 with an equal sample size. The mean differences of daily $PM_{2.5}$ concentration between the year 2019 and 2020 during the lockdown period were significantly lower (at α=0.01) during the same time in Delhi, Dhaka, Kathmandu, and Kolkata. The mean differences of daily $PM_{2.5}$ concentration between 2020 and 2018 were also significantly lower in all those cities except Dhaka.

Figure 5 depicts the diurnal changes of $PM_{2.5}$ in selected cities from 2018-2020 at the same time of April and May. The nighttime air pollution (8 pm-6 am) is higher than during the day in all cities except Kolkata. Restriction of the heavy vehicle (long road trucks) occurs only throughout the day in Delhi, Dhaka, and Lahore year around (Nagar et al., 2017; Nayeem et al., 2020; Rasheed et al., 2015; Gorai et al., 2018). The primary cause of higher pollution levels at night in these cities may be heavy vehicle traffic. Since there is little restriction on heavy traffic in Kolkata, $PM_{2.5}$ is similar during the day and night (Bera et al., 2020). The pollution levels increase at night in

Kathmandu because of the slopes and orientation of the mountains (Mahapatra et al., 2019).

Table 5 shows the mean differences of diurnal $PM_{2.5}$ concentration between 2019 and 2020, and 2018 186 and 2020 were also significantly lower (at α=0.01) according to Tukey's post hoc comparison. During the COVID-19 lockdown in these cities, nighttime entry to the central city was open for these vehicles. The mean differences were not significant at night (8 pm-6 am) in Delhi, Dhaka, and Lahore, possibly because the traffic conditions were similar to previous years. The study found pollutant levels high at nighttime in the Kathmandu valley because of the surrounding mountains (Mahapatra et al., 2019).

Table 4. Summary of Tukey's post hoc multiple comparisons between hourly $PM_{2.5}$ and years

Location	(I) Year	(J) Year	Mean difference (I-J)	Std. Error
Delhi	2020	2018	-26.3[a]	4.9
		2019	-38.1[a]	4.9
Dhaka	2020	2018	-7.2	4.6
		2019	-15.2[b]	4.6
Kathmandu	2020	2018	-13.9[b]	3.9
		2019	-21.2[a]	3.9
Kolkata	2020	2018	-15.4[a]	2.2
		2019	-11.5[a]	2.2

[a] The mean difference is significant at α=0.001
[b] The mean difference is significant at α=0.01

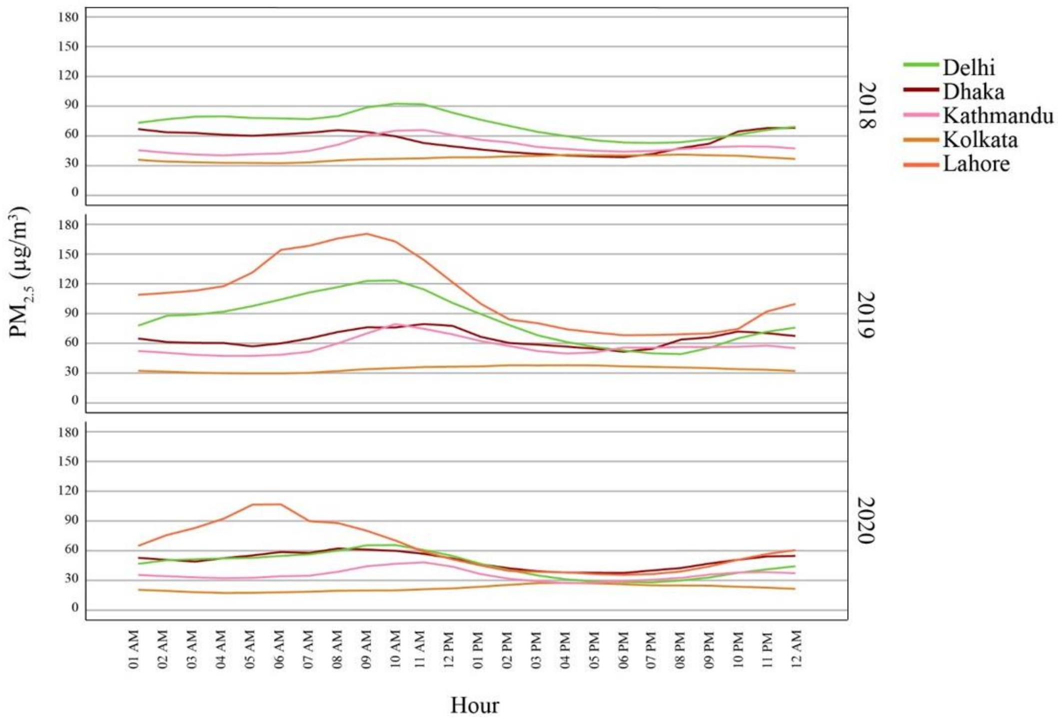

Figure 5. Diurnal changes of $PM_{2.5}$ in different cities from 2018-2020 at same time (April-May)

Table 5. Summary of Tukey's post hoc multiple comparisons between diurnal $PM_{2.5}$ and years

Location		(I) Year	(J) Year	Mean difference (I-J)	Std. Error
Delhi	Night (8 pm-6 am)	2020	2018	-11.42	4.47
			2019	-4.51	4.47
	Day (6 am-8 pm)	2020	2018	-35.11[a]	5.21
			2019	-37.62[a]	5.21

Table 5. Summary of Tukey's post hoc multiple comparisons between diurnal $PM_{2.5}$ and years (cont.)

Location		(I) Year	(J) Year	Mean difference (I-J)	Std. Error
Dhaka	Night (8 pm-6 am)	2020	2018	-3.18	4.37
			2019	-7.70	4.36
	Day (6 am-8 pm)	2020	2018	-17.01[b]	5.20
			2019	-14.56[a]	5.11
Kathmandu	Night (8 pm-6 am)	2020	2018	-9.70	3.70
			2019	-6.25	3.72
	Day (6 am-8 pm)	2020	2018	-17.88[a]	2.48
			2019	-21.90[a]	2.49
Kolkata	Night (8 pm-6 am)	2020	2018	-15.39[a]	2.21
			2019	-7.86[a]	2.17
	Day (6 am-8 pm)	2020	2018	-6.74	3.39
			2019	-7.36	3.28

[a] The mean difference is significant at α=0.001
[b] The mean difference is significant at α=0.01

Air pollution concentrations in the Kathmandu valley increased gradually after sunset (Shrestha et al., 2002). In Kolkata, the nighttime mean differences for both the cases (2018-2020 and 2019-2020) were significantly lower (at α=0.01). No restriction on vehicle movement and the emission from the nearby coal power plant of Kolkata might be the reasons for high pollution in the daytime (Bera et al., 2020).

4. CONCLUSION

The present study found a significant reduction of daily tropospheric columnar NO_2 and $PM_{2.5}$ concentrations in all the cities compared to previous years during the same timeline.

- The tropospheric columnar NO_2 values were reduced between 9% and 48% in the cities studied.
- The daily mean $PM_{2.5}$ values were reduced between 13% and 46% in the cities studied.
- The diurnal pattern of $PM_{2.5}$ showed significant improvement of between 15% and 38% during the day in Delhi, Dhaka, and Kathmandu due to traffic restrictions.

Abatement of tropospheric columnar NO_2 and $PM_{2.5}$ occurred because of the restrictive actions imposed to reduce the population's mobility and shut down many commercial establishments and industries. The temporary decrease in the concentrations of pollutants is not a sustainable way to improve the environment. The effect of the lockdown on air pollution provided a unique opportunity to analyze the effects of various emission sources and further assess air quality policies. Traffic was significantly less during the lockdown in each of the selected cities. Air quality can be improved by increasing mass transit or restricting vehicles in certain areas of each city. The closing of companies resulted in emissions reduction from manufacturing and industrial facilities. Introducing more fuel-efficient transportation systems and improved pollution strategies for industries would improve air quality permanently. Improvement in industrial emission standards could assist in these cities reaching similar air quality during normal operations. This study was not able to compare overpass sensor data to tropospheric columnar NO_2 sensor data. In addition, a single monitoring station of $PM_{2.5}$ cannot represent an entire city. This study indicates the relative impact on tropospheric columnar NO_2 and $PM_{2.5}$ resulting from the COVID-19 lockdown.

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