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Assessment of variations of air pollutant concentrations during the COVID-19 lockdown and impact on urban air quality in South Asia

Rehana Khan a, b, Kanike Raghavendra Kumar c, a, *, Tianliang Zhao a, *

a Collaborative Innovation Centre on Forecast and Evaluation of Meteorological Disasters, Key Laboratory of Meteorological Disaster, Ministry of Education (KLME), International Joint Laboratory on Climate and Environment Change (ILCEC), Key Laboratory for Aerosol-Cloud-Precipitation of China Meteorological Administration, School of Atmospheric Physics, Nanjing University of Information Science and Technology, Nanjing 210044, Jiangsu, China
b Department of Physics, Higher Education, Government of Khyber Pakhtunkhwa, Peshawar 25000, Pakistan
c Department of Physics, Koneru Lakshmaiah Education Foundation (KLEF), Vaddeswaram, 522502 Guntur, Andhra Pradesh, India

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ABSTRACT

Quantifying the variations of atmospheric aerosols and trace gas concentrations with the impact of lockdown due to the Coronavirus disease of 2019 (COVID-19) pandemic is crucial in understanding urban air quality. For this purpose, we utilized the multi-instrumental approach of satellite remote sensing and reanalysis model data to examine the spatial and temporal patterns of major air pollutants during December 2019–June 2020 in South Asia. The lockdown has led to a considerable decrease in aerosol optical thickness (AOT) over South China (−18.92%) and Indo-Gangetic Plain (IGP; −24.29%) compared to its ordinary level for a couple of weeks. Noticeable reductions in tropospheric NO2 are observed over the Pearl River Delta (PRD; −0.3/cm²) followed by Central China (CC) with −0.21/cm² and IGP (−0.085/cm²), and the lowest (−0.0008/cm²) in the Tibetan Plateau (TP) region. The changes observed in PM2.5 and SO2 levels (from −58.56% to −63.64%) are attributed to the decrease in anthropogenic emissions, vehicular exhaust, and industrial activities. However, the BC concentrations are reduced by approximately halved of its ordinary levels in the IGP (2.28 μg/m³) followed by YRD (1.56 μg/m³), CC (1.5 μg/m³), NCP (1.29 μg/m³), and PRD (0.78 μg/m³) regions. The total column O3 predominantly increased from 262.68 to 285.53DU, 323.00 to 343.00DU, and 245.00 to 265.00DU in the YRD, NCP, and IGP areas. This is mainly associated with solar radiation, meteorological factors, and an unprecedented reduction in NOx during the lockdown period.

1. Introduction

The world, presently, is facing problems due to climate change and the deterioration of air quality (WHO, 2018). The abrupt outbreak of the Coronavirus disease 2019 (COVID-19) pandemic produced unprecedented societal impacts over the Asian continent and has drawn considerable attention since the year 2019 till today. Since the detection of the realm’s first case in late December 2019 (March 2020) in China (Pakistan and India), the concerned governments have decided to declare a state of a health emergency. The regional areas were started locked down on 23rd January 2020 in Wuhan, Hubei province (China), and 25th March 2020 in Pakistan and India. Later on, the lockdown was imposed in the rest of the countries in Asia such as Nepal and Bangladesh, which has been

* Corresponding authors.
E-mail addresses: rkanike@kluniversity.in (K.R. Kumar), tlzhao@nuist.edu.cn (T. Zhao).

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referred to as the largest attempted quarantine in human history (WHO, 2021). Responding to the ongoing outbreak, the majority of industrial and commercial activities including regional transportation have been banned for three weeks at an early stage in China. Also, the same sanitary state of emergency was extended to almost all the regions of Asia until May 2020, which later on spread to the entire world. As on the current version of paper writing (24 May 2021), a total of 166.34 million cases of COVID-19 had been detected and confirmed across the globe, with almost 3.44 million deaths, in which South Asia shares more than 30.33 million registered cases and 0.377 million deaths are recorded (WHO, 2021).

Over the past few years, the fast-growing economy, urbanization, industrial development, and associated growth in emission sources have drawn a huge impact on the air quality in Asia (Wang et al., 2020; Shen et al., 2021; Bao and Zhang, 2020; Khan et al., 2019; Zheng et al., 2019). The major source of pollutants includes vehicular emission, industrial activities, and domestic fuel burning (Khan et al., 2019). However, the emissions from both stationary (industrial) and mobile sources, such as ground-level ozone, lead, nitrogen dioxide (NO₂), particulate matter with aerodynamic diameters of 2.5 and 10 μm (PM₂.₅, PM₁₀), ammonia (NH₃), sulfur dioxide (SO₂), and carbon monoxide (CO), are the primary air pollutants in the atmosphere. These pollutants are closely associated with heart disease, lung cancer, and chronic respiratory disorders as estimated to be the cause of 4.2 million fatalities per year owing to worse air pollution (WHO, 2018). Also, the trace gases are estimated to be precursors of organic and inorganic regional aerosols that are responsible for high pollution levels, and major environmental issues at several urban locations of South Asia (WHO, 2018).

Given the immense global concern, till now, several studies over Asia (Ahmadi et al., 2020; Jahangiri et al., 2020; Sharma et al., 2020; Kanniah et al., 2020; Kerimray et al., 2020; Yadav et al., 2020), China (Muhammad et al., 2020; Xu et al., 2020; Bao and Zhang, 2020; Beig et al., 2020), and in Europe (Siciliano et al., 2020; Tobías et al., 2020; Nakada and Urban, 2020; Conticini et al., 2020; Martínez et al., 2020) have been devoted to the ongoing pandemic scenario and its impact on air quality. According to Finland’s Centre for Research on Energy and Clean Air (FCRECA) report on CO₂ and European Space Agency (ESA) earlier estimation on NO₂, the significant decline (found in both the air precursors) will improve the air quality on a local and regional basis (Bao and Zhang, 2020). In China, by the Institute of Environmental Science and Meteorology (IESM), a substantial decrease in PM₂.₅ and PM₁₀ concentrations were observed attributed to the decrease in anthropogenic emissions, and the role of regional meteorology during the pandemic period (Wang et al., 2020). Recently, a considerable decrease in aerosol optical thickness, AOT (−9.8%), CO (−8.57%), and PM₂.₅ (−7.39%) was found at several urban locations in Pakistan (Khan et al., 2021). Further, according to the Central Pollution Control Board (CPCB) of India, the decrease of concentration of major air pollutants (PM₂.₅, PM₁₀, and CO with −47%, −41%, and −27%, respectively) were noticed during the lockdown period (Mandal et al., 2021) at urban cities in India. All these studies have examined and documented the significant role of lockdown (COVID-19) resulted in the improvement of air quality using ground and space-borne sensors. However, it is still needed to assess the atmospheric influence of the ongoing pandemic in different regions in South Asia to reveal its implications on pollution control strategies.

Earlier, South Asia had been confronting severe air pollution problems as the continent was captured with 8.58% of the population of the world (WPY, 2020), while its contribution to air pollution was more than 45% globally (WHO, 2018). The impact of air pollution has been a major problem especially in the recent decade and found responsible for 7 million premature deaths annually, of which South Asia accounts for (34%) 2.4 million fatalities per year (WHO, 2018; Zheng et al., 2019). In a hypothetical scenario, the mean air pollution level over South Asia exceeding, the limit set by the WHO (10 and 20 μg m⁻³ for PM₂.₅ and PM₁₀, respectively) by 5–10 times, leads to 30–45 preventable deaths per million capita (WHO, 2018).

Henceforth, the present work elucidates the effectiveness of regional lockdown during the Pandemic (COVID-19) on air quality in Asia. The impact of lockdown due to COVID-19 on the atmosphere is mainly visualized in major aerosol hotspot regions in Asia namely, Indo-Gangetic Plain (IGP) (covers Pakistan, India, Nepal, and Bangladesh), Tibetan Plateau (TP), Central China (CC), Pearl River Delta (PRD), North China Plain (NCP), and Yangtze River Delta (YRD) regions located in China. To analyze the present situation, we have

![Geographical map of South Asia](image-url)
concentrations (Sharma et al., 2020). Besides, the OMI Aura-derived daily total column ozone ($O_3$) and trace gases ($O_3$, $NO_2$, $CO$, $SO_2$) to understand their spatial and temporal distributions at the selected regions in Asia.

2. Study area

The study area (South Asia) considered here covers the land area with the geographical coordinates between $23^\circ$–$55^\circ$ N and $60^\circ$–$130^\circ$ E. The study area is well-known for its complex terrain, topography and meteorological conditions, and well-mixed urban environments (Fig. 1). Further, the dense population, industrialization, and stable economy are the additional features that make this region prominent among other subcontinents. Besides, the study area serves the globe with different types of natural/anthropogenic aerosols and trace gas pollutants from the past several decades (Kanniah et al., 2020). However, the frequent and intensive human activities have a large impact on the air quality by anthropogenic emissions, fossil fuel/biomass burning, and continuous emissions from the power plants, oil refineries that led to the deterioration of air quality and human health (Muhammad et al., 2020).

The study domain experiences a dry climate with significant regional climatic variations influenced by several factors such as Typhoons, El-Nino Southern Oscillation (ENSO), Indian Ocean Dipole (IOD) and monsoon circulation dominates across the southern domain. The seasonal transition in precipitation usually occurs from the winter (DJF) to summer-monsoon (JJA) in May, characterized by relatively high temperature and relative humidity (RH) in South Asia (Khan et al., 2019). The local monsoon seasons are generally characterized by low AOT attributed to enhanced precipitation causing large wet deposition of aerosols. In contrast, the pre-monsoon seasons demonstrated high aerosol loadings due to increased anthropogenic activities and reduced precipitation (Khan et al., 2019).

Temperatures over South Asia are varied from mild to hot in the range of 20 $^\circ$C–46 $^\circ$C with the lowest (highest) values generally observed during winter (summer). RH generally signifies seasonal heterogeneity being high during summer and low during winter. The study region is moderately drier during winter (DJF) followed by the summer (MAM) period, being more pronounced in the southwestern part of China. Further, the winter is dominated by west-southerlies carrying a significant amount of natural dust from the Cholistan and the Thar Deserts (Khan et al., 2019). The pre-monsoon (or summer; JJA) and post-monsoon (SON) seasons are dominated by south-easterlies enhance the production and transportation of marine aerosols and smoke particles from the southeast Indian Ocean and Bay of Bengal, respectively. The magnitude of RH increases as we move from Karachi through Lahore to Kanpur (IGP) and from Beijing to Taihu (NCP) (Khan et al., 2019).

3. Data and methods

The database used in the present work is obtained from three Earth Observation System (EOS) satellites namely; MODIS-Aqua, AIRS, OMI, and the reanalysis model data from the MERRA-2.

The Moderate-resolution Imaging Spectroradiometer (MODIS) is a global imaging sensor that has been flying aboard the Terra and Aqua satellites, which is an important part of NASA’s EOS, since May 2000 and July 2002, respectively. It provides several aerosol products over the ocean and land (Sayer et al., 2013). The sensor measures radiances at the spatial resolutions of 0.25, 0.5, and 1.0 km, depending mainly on the selected waveband. The aerosol products retrieved from MODIS have proven to be reliable over oceans, dark and bright land surfaces after recent improvements in the aerosol retrieval algorithms (Hsu et al., 2004). Over dark surfaces (vegetative land and oceans), AOT is retrieved using the Dark-Target (DT) algorithm (Sayer et al., 2013); however, Deep Blue (DB) algorithm is used for bright surfaces (Levy et al., 2013). The complete details about DT and DB algorithms can be found in Levy et al. (2013). In this study, we have used the MODIS-Aqua merged DT and DB Collection 6.1 Level 3 daily AOT at 550 nm (AOT$_{550}$) over the land and ocean. The dataset and more details are available at http://modis.gsfc.nasa.gov/.

Atmospheric Infrared Sounder (AIRS), a weather forecast instrument launched on 4th May 2002 (onboard NASA’s Aqua platform) is capable of monitoring the global tropospheric CO mole fraction (in ppbv; parts per billion volume) (Chahine et al., 2005). The AIRS cross-track scanning grating spectrometer offers atmospheric vertical profiles with a field of view of 45 km nadir through a 1650 km swath (Aumann et al., 2003). The sensor provides broad spectral coverage in the range of 3.75 to 15.4 $\mu$m with 2378 different channels. Further, the AIRS enables 70% of the global retrieval twice per day, nearly in both hemispheres with an angle range of 45°–80°. AIRS data sets are validated using the ground-based total column measurements in Russia and Australia (Yurganov et al., 2008b) and agreement between AIRS and air-borne measurements was found within an average of 10–15 ppbv. This agreement between the space-borne AIRS and ground-based total column CO measurements (not shown here) enables us to use AIRS in the present work to investigate the spatial and temporal levels of CO for the PLD (pre-lockdown) and DLD (during lockdown) phases.

The Ozone Monitoring Instrument (OMI), a nadir-viewing spectrometer onboard NASA’s Aura satellite and is the first sensor capable of working on the UV and visible spectrum with a charge-coupled device, enabling daily global monitoring of $O_3$, $NO_2$, and $SO_2$ concentrations (Sharma et al., 2020). Besides, the OMI Aura-derived daily total column ozone ($O_3$), $NO_2$ and planetary boundary layer (PBL) observed sulfur dioxide ($SO_2$) were analyzed in the present work. Further, the OMI retrieved $O_3$, $NO_2$, and $SO_2$ data sets are available from NASA’s GES-DISC at http://disc.gsfc.nasa.gov/.

The Modern-Era Retrospective analysis for Research and Applications of version 2.0 (MERRA-2) is a global modeling-GMAO product sponsored by NASA and is capable of providing a regularly gridded and homogeneous data set of the atmosphere from

utilized and executed data obtained from the multiple space-borne satellites such as Moderate-resolution Imaging Spectroradiometer (MODIS), Ozone Monitoring Instrument (OMI), and Atmospheric Infrared Sounder (AIRS), and reanalysis model data from the Modern-Era Retrospective analysis for Research and Application of version 2.0 (MERRA-2) for the above-mentioned aerosol hotspot regions in Asia. To attempt and ascertain the significant consequences of lockdown (pre and post) periods, we obtained data for the concentrations of aerosols (AOT, BC, PM$_{2.5}$) and trace gases ($O_3$, $NO_2$, $CO$, $SO_2$) to understand their spatial and temporal distributions at the selected regions in Asia.
1980 to the present (Gelaro et al., 2017; Khan et al., 2021). The model uses a new version of the GEOS-5 (Goddard Earth Observing System Model, version 5) data assimilation system to synthesize regular time series of gridded data, with a spatial resolution of 0.5° × 0.625° (latitude × longitude) at 72 pressure levels (from the surface to 0.01 hPa) with both instantaneous and time-averaged (hour, 3-h, and month) data (Gelaro et al., 2017). Among the advantages of MERRA-2, (in comparison with its previous version) are an improved presentation of the hydrological cycle, cryosphere-stratosphere processes, atmospheric ozone, as well as joint assimilation of aerosol radiative forcing and meteorological fields (Buchard et al., 2017). However, the aerosol assimilation system in MERRA-2 uses AOT measurements from satellite instruments (such as MODIS, MISR, AVHHR) and also from the ground-based Aerosol Robotic Network (AERONET) stations (Khan et al., 2021). The surface mass concentration of hourly BC and column mass density of PM$_{2.5}$ observed from MERRA-2 were analyzed in the present work, which is open access and free for the public (https://disc.sci.gsfc.nasa.gov/). An overview of the MERRA-2 modeling system and a more detailed description of aerosols in the MERRA-2 database can be found in Gelaro et al. (2017).

The datasets from the above sensors were downloaded for seven months from December 2019 to June 2020 to understand the changes in concentration levels of air pollutants (aerosols and trace gases) and evaluate the impact of lockdown on regional air quality over South Asia.

4. Results

4.1. Variations in AOT

As one of the major optical characteristics of aerosols, the MODIS-derived column AOT distributions are examined to reveal possible changes in air quality over South Asia (Fig. 2a-d). Since the data set is analyzed and compared for both the study periods i.e., pre-lockdown (PLD from 01 December 2019 to 22 January 2020), and during-lockdown (DLD from 24 January to 29 February 2020). However, the lockdown (due to COVID-19 Pandemic) started slightly later in the IGP regions of India, Pakistan, Bangladesh, and Nepal. Hence, the period of study for the PLD and DLD days is considered from 16 January to 24 March 2020 and 25 March to 31 May

**Fig. 2.** The spatial distribution of AOT$_{550}$ measured by the MODIS-Aqua in South Asia: a) 1st December 2019 to 22nd January 2020 (Pre-lockdown) and b) 23rd January to 29th February 2020 (during-lockdown) for the Chinese regions. Likewise the bottom panel represent the variation in columnar aerosol load (AOT$_{550}$ in IGP areas) between 16th January to 24th March 2020 (Pre-lockdown); and d) bottom-right: 25th March to 31st May 2020 (during-lockdown). The blank spaces in the figures are areas where calculation could not be extended because of missing values in MODIS-Aqua data set. Colors indicate the range of distribution per land cover in the grid cell. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
2020. Surprisingly, the decrease in AOT values over most of the study areas is not evident as was expected because of the proportional increase in domestic activities. Over the lockdown period, a normal decrease in aerosol loading (<0.2) was usually found in the economically and industrially developed areas of upper IGP, and urban regions of NCP, and CC (Figs. 2a-d). On contrary, TP exhibited marginal changes in AOT (~0.01% and ~3.03%) (Fig. 2; Table 1), specifically attributed to the fact that the study region is suburban and less developed, compared to the rest of the study areas. However, the TP region is less affected by the seasonal biomass plumes transported from the surrounding regions (including East China and upper IGP) is another reason for the present results. It is to be noted that the AOT values are mainly affiliated with the anthropogenic and regional local emission sources (Kamraiah et al., 2020). A significant increase in AOT (0.42) was found over the PRD leading to the fractional change of 15–17% in column AOT during DLD (Fig. 2, Table 1) attributed to the domestic anthropogenic emissions for large-scale heating and unfavorable meteorological conditions (Wang et al., 2020). However, the role of climate and local meteorology was not taken into consideration for the present work as the study was conducted in due course of a short period. Regional mean AOT experienced a reduction of ~0.17 over IGP corresponding to a fractional change of ~24.2%. It can also be observed that, usually, the decline in AOT was not higher compared to the atmospheric trace gases (Fig. 2). The same is attributed to the fact that (i) anthropogenic activities are not only interlinked with industry, transportation, power plants, and energy sources, etc., rather than for the lockdown phase; but all these sources were somehow, replaced by residual cooking, heating including agricultural activities, that led to a general increase in atmospheric aerosol and pollutant levels. (ii) It can be justified by some other possible reasons including topographical and meteorological factors as precipitation, relative humidity, and geographical location, and so on (Shen et al., 2021; Bao and Zhang, 2020). On contrary, the dust extinction AOT exhibited marginal changes i.e., −0.6 to −0.2 in North China regions and comparatively lower distribution in the middle and central parts of IGP i.e., −0.4 to −0.33 (figure not shown here) for the DLD phase. The seasonal dust episode during the study period underscores the

| Table 1 | Mean variation of aerosols and trace gases concentration observed during December 2019–January 2020 (pre-lockdown) and January–March 2020 (during the lockdown) in six urban regions namely; YRD (Yangtze River Delta), NCP (North China Plain), PRD (Pearl River Delta), CC (Central China), TP (Tibetan Plateau), and IGP (Indo-Gangetic Plain) of South Asia. |
|---------|-------------------|------------------|-----------------|-----------------|-----------------|
| Study Site | Air Pollutant (Unit) | Pre-lockdown | During- Lockdown | Difference | % variation |
| YRD | AOT | 0.60 ± 0.37 | 0.50 ± 0.20 | −0.1 | −16.67 |
| PM2.5 (µg/m³) | 31.2 ± 8.8 | 21.7 ± 2.3 | −11.5 | −36.86 |
| SO₂ (DU) | 0.09 ± 0.07 | 0.04 ± 0.03 | −0.05 | −55.56 |
| NO₂ (1/cm²) | 1.28 ± 0.52 | 0.94 ± 0.15 | −0.35 | −27.34 |
| CO (ppbv) | 181 ± 21.0 | 156.6 ± 26.0 | −24.4 | −13.48 |
| O₃ (DU) | 262.68 ± 46.40 | 285.53 ± 46.02 | 22.85 | 8.7 |
| BC (µg/m³) | 4.34 ± 1.89 | 2.78 ± 1.12 | −1.56 | −35.94 |
| NCP | AOT | 0.52 ± 0.29 | 0.50 ± 0.31 | −0.02 | −3.85 |
| PM2.5 (µg/m³) | 28.9 ± 7.4 | 18.1 ± 5.3 | −10.8 | −37.37 |
| SO₂ (DU) | 0.13 ± 0.11 | 0.07 ± 0.05 | −0.07 | −53.85 |
| NO₂ (1/cm²) | 1.26 ± 0.68 | 0.93 ± 0.22 | −0.34 | −26.98 |
| CO (ppbv) | 186.0 ± 34.0 | 170.2 ± 33.0 | −15.8 | −8.49 |
| O₃ (DU) | 323 ± 51.22 | 343 ± 71.55 | 19.64 | 6.08 |
| BC (µg/m³) | 3.90 ± 2.14 | 2.61 ± 1.21 | −1.29 | −33.08 |
| PRD | AOT | 0.35 ± 0.21 | 0.42 ± 0.15 | 0.07 | 16.67 |
| PM2.5 (µg/m³) | 18.0 ± 6.4 | 12.2 ± 1.4 | −6.8 | −37.78 |
| SO₂ (DU) | 0.11 ± 0.14 | 0.03 ± 0.07 | −0.04 | −63.64 |
| NO₂ (1/cm²) | 1.00 ± 0.45 | 0.70 ± 0.17 | −0.3 | −30.00 |
| CO (ppbv) | 179 ± 25.0 | 163.3 ± 55.0 | −15.7 | −8.77 |
| O₃ (DU) | 233.97 ± 47.82 | 252.32 ± 50.56 | 18.36 | 7.85 |
| BC (µg/m³) | 2.92 ± 1.17 | 2.14 ± 0.62 | −0.78 | −26.71 |
| CC | AOT | 0.37 ± 0.20 | 0.30 ± 0.30 | −0.07 | −18.92 |
| PM2.5 (µg/m³) | 40.3 ± 0.5 | 16.7 ± 6.1 | −23.6 | −58.56 |
| SO₂ (DU) | 0.10 ± 0.12 | 0.05 ± 0.04 | −0.05 | −50.00 |
| NO₂ (1/cm²) | 0.44 ± 0.23 | 0.23 ± 0.12 | −0.21 | −47.73 |
| CO (ppbv) | 161.0 ± 50 | 163.1 ± 41.0 | 1.90 | 1.17 |
| O₃ (DU) | 285.03 ± 43.69 | 308.39 ± 45.12 | 23.37 | 8.20 |
| BC (µg/m³) | 4.38 ± 1.63 | 2.88 ± 1.17 | −1.50 | −34.25 |
| TP | AOT | 0.33 ± 0.16 | 0.32 ± 0.17 | −0.01 | −3.03 |
| PM2.5 (µg/m³) | 0.000048 ± 0.0001 | 0.000077 ± 0.0001 | −0.000031 | −22.92 |
| SO₂ (DU) | 0.08 ± 0.07 | 0.06 ± 0.04 | −0.02 | −25 |
| NO₂ (1/cm²) | 0.03 ± 0.02 | 0.03 ± 0.02 | 0.0008 | 2.67 |
| CO (ppbv) | 101.2 ± 30 | 91.1 ± 32.0 | −10.1 | −9.98 |
| O₃ (DU) | 263.27 ± 54.60 | 278.18 ± 56.33 | 14.91 | 5.66 |
| BC (µg/m³) | 0.06 ± 0.03 | 0.06 ± 0.03 | −0.000013 | −0.016 |
| IGP | AOT | 0.70 ± 0.23 | 0.53 ± 0.13 | −0.17 | −24.29 |
| PM2.5 (µg/m³) | 97.9 ± 6.2 | 69.7 ± 11.7 | −28.2 | −28.8 |
| SO₂ (DU) | 0.09 ± 0.07 | 0.07 ± 0.02 | −0.03 | −33.33 |
| NO₂ (1/cm²) | 0.22 ± 0.18 | 0.13 ± 0.07 | −0.085 | −38.64 |
| CO (ppbv) | 158.2 ± 41.0 | 131.1 ± 52.0 | −27.1 | −17.13 |
| O₃ (DU) | 245 ± 51.78 | 265.55 ± 46.19 | 20.55 | 8.39 |
| BC (µg/m³) | 4.67 ± 1.12 | 2.39 ± 0.66 | −2.28 | −48.8 |
importance of the regional and geographical factors in the study area.

Fig. 3 reveal the regional trend in hourly mean aerosol load (AOT) from the reanalysis MERRA-2 data product. Potential differences in the time series of AOT distribution during each period were separated by vertical lines. Nearly all the study areas (Fig. 3) witnessed a significant declining trend for the DLD phase including the last week of post-lockdown, being strongly related to the significant characteristics of each region. Also, the impact of regional emission sources (traffic/industrial), and the relative influences from topography and meteorology cannot be ignored. In general, the maximum decline in AOT appears during DLD over IGP areas, with a mean of $0.53 \pm 0.13$ followed by the YRD ($0.50 \pm 0.20$) and CC ($0.30 \pm 0.30$), respectively. And, a minimum variation was observed over the NCP/PRD regions ($0.07–0.02$) (Fig. 4, Table 1). However, the AOT levels were found to be gradually regained its initial values during the post-lockdown period over all the study areas, except TP. The average solar radiation is notably higher in the TP and Northwest regions of China leads to the abnormal fluctuation in column aerosol over the TP area (Shen et al., 2021).

4.2. PM$_{2.5}$ and BC concentrations

PM$_{2.5}$ is the primary pollutant that is associated with atmospheric air quality mitigation across Asia. Besides domestic sources, (residential heating, cooking), PM mainly carries both the organic and inorganic particles, mostly originated from industrial activities,
regional traffic, and secondary atmospheric processes. Based on the comparison of an average distribution (Figs. 5, 6; Table 1) during the PLD and DLD phases, the two pollutants Black Carbon (BC) and PM$_{2.5}$ were identified with significant low values in the urban areas of IGP (Fig. 6c-d), the upper part of CC (Fig. 6a-b), and NCP (Fig. 5a-b). Whereas, the suburban and less developed areas of TP featured with negligible distribution (Figs. 5a-b, 6a-b), affirming the distinct regional topography and elevation, high altitude, less population, and industrialization compared to the rest of the studied locations. By taking percentage variation, it is estimated that the PM$_{2.5}$ decreased by $37.78\%$ and $37.37\%$ in the PRD and NCP regions, with the relative decrease in BC as $-26.71\%$ and $-33.08\%$, respectively. For the background stations in CC, the percentage decline in PM$_{2.5}$ (BC) was reported comparatively high $-58.56\%$ ($-34.25\%$) (Fig. 4, Table 1). Similar decrease in PM$_{2.5}$ has also been recorded recently in other (urban and economically developed) regions of China ($-25\%$ to $-31\%$), Delhi ($-43\%$ to $-50\%$), and Malaysia ($-23\%$ to $-32\%$) (Bao and Zhang, 2020; Kanniah et al., 2020; Sharma et al., 2020). In contrast, the hotspot of BC was evident over the IGP regions for the DLD phase, where the decline in regional mean BC concentration was about 2–3 times higher than that in other areas of the study domain (Fig. 6c-d). The possible features that explain this phase of the declining trend in BC include the complex nature of secondary aerosols, static/dry weather conditions, and the PLD period that has created a large difference among both the data sets (PLD/DLD).
Fig. 5. Same as in Fig. 2, but for the column mass density of PM$_{2.5}$.

Fig. 6. Same as in Fig. 2, but for the surface mass concentration of BC retrieved from the MERRA-2 reanalysis.
BC is one of the important air quality indicators and is primarily emitted in both natural and anthropogenic soot, seen common in the atmosphere of South Asia. It’s mostly originating from incomplete combustion sources (fossil/biofuel, and biomass). The PM$_{2.5}$ and BC concentrations trace each other in an almost similar way with the variation of 26%–40% at all the study locations in South Asia. However, the BC levels in TP were substantially lower than the rest of the study areas in South Asia, with a daily mean of 0.06 ± 0.01 μg/m$^3$ and no significant percentage difference is observed compared to the other regions (Table 1, Fig. 4). Besides regional lockdown, several other factors and phenomena can be interlinked with the present results including global solar radiation, atmospheric stability, photochemical reactions, long-range transport, geographical location, local/regional meteorology, and the actual concentration of aerosol/trace gases before the physical removal process.

4.3. Changes observed in CO, SO$_2$, and O$_3$ concentrations

Carbon Monoxide (CO), Sulfur dioxide (SO$_2$) and Ozone (O$_3$) species arise from different anthropogenic sources. Figs. 7-9 present the observed spatial distribution of mole fraction (CO), SO$_2$ column amount (PBL), and total column ozone (O$_3$) retrieved from the AIRS and OMI satellites, respectively. It is known that CO (O$_3$) is directly (indirectly) associated with the sources of vehicular road traffic and industrial emissions. Considering the uneven distribution of column SO$_2$ for the DLD phase, the average change in percentage concentration ranged from 25.0% to 63.64% in China with the highest decline observed in PRD (−0.07 DU) followed by the CC/YRD (−0.05 DU), the NCP (−0.07 DU), and the lowest decrease in the TP (−0.02 DU) region of China (Table 1, Fig. 4). A significant reduction in trace gas concentrations is also seen in suburban and less populated rural sites of South China. However, the notable decrease is estimated in CO levels over the IGP with −17.13% for the DLD phase attributed to the various restriction measures introduced due to the pandemic lockdown on a local and regional scale. The results are consistent with previous observations reported in some other parts of South Asia (Sharma et al., 2020; Mahato et al., 2020). A lower decrease was observed in SO$_2$ (25%) and CO (−9.98%) over the TP region is affiliated with the clean environment and geographical location compared to the rest of the study areas for the DLD period (Figs.7-8). By contrast, the mean values of daily surface ozone (O$_3$) increased over densely populated and urban background areas of the YRD, CC, NCP, and PRD varied between 5.66% and 8.39%. Whereas a maximum was reported over the IGP (8.39%), and a minimum of 5.66% was recorded in the TP areas for the DLD period. The same is related to an unprecedented reduction in NOx emissions (discussed in the following section) during the study period. It should be added that the visible differences in all these pollutants levels (during DLD about PLD) are attributed to many factors including the particle size, its chemical composition, and local environment, temperature, relative humidity, and the tropospheric residence time.

4.4. Changes in NO$_2$ levels

NO$_2$ is a significant gaseous precursor, with global, regional, and local impacts on air quality. Fig. 10a-b shows the observed spatial
Fig. 9. Same as in Fig. 2, but for the daily mean total column Ozone.

Fig. 8. Same as in Fig. 2, but for the column amount of $SO_2$ (PBL) measured by OMI.
distribution of tropospheric column NO$_2$ in South Asia over both the regions: China (Fig. 10a-b) and IGP (Fig. 10c-d) for PLD and DLD. In general, a high concentration of NO$_2$ was observed over central and northeastern regions of China including, upper IGP (India and Nepal), with a significant decline for the DLD phase. Notable reductions were specifically seen over areas affected by anthropogenic and industrial emissions sources including, seasonal biomass burning with the highest in the CC (−47.73%) followed by the IGP (−38.64%), PRD (−30.00%) and margin to least (−2.67%) in the TP region. Previous studies (Wu et al., 2020; Li et al., 2020), attributed to the decline of NO$_2$ with the mutual correlation that existed between NOx, solar radiation, and the photochemistry of column ozone. Although, a decrease in NOx and SO$_2$ precursors from industrial and manufacturing sectors have long been considered as the normal aggregate in implementing regulatory policies by China, India, and Pakistan. However, the present situation highlights the prominent change in the most urban and industrial domains of South Asia.

5. Discussion

The data presented in this manuscript revealed a decrease in the atmospheric aerosol and trace gases concentrations in South Asia for the DLD-phase (January and February 2020) in China and in a similar way in IGP (March–May 2020). The TP and North China regions showed a marginal to lower decrease in the spatial and temporal extent, despite reports of greatly reduced anthropogenic activities (industrial, transportation) during the DLD phase. Also, the increase in AOT across the PRD during DLD observed from both the MODIS satellite and MERRA-2 reanalysis data suggests that vehicular and traffic measures may have little effect in controlling regional air pollution. The AIRS retrieved observations showed a slight decrease in mole fraction of CO levels over the study areas compared to other pollutants, with some increase (1.17%) observed in Central China relevant to the PLD phase. The exact reason behind this variation is not immediately obvious, however, some factors considered being responsible, including air pollutant lifetime, regional topography and elevation, meteorology and the foremost one may be enhanced production of secondary particulates during the lockdown period. The tropospheric NO$_2$ levels by OMI sensor showed a significant decline (25–40%) during the DLD period in most of the study areas. A maximum of NO$_2$ was observed in the IGP and CC regions due to a decrease in the road and air traffic, industries, and power plants emissions during the DLD phase, which account for a decrease of more than 79.79% of NOx in South Asia (Wu et al., 2020; Li et al., 2020; Bao and Zhang, 2020).

The satellite observations revealed a significant decrease in PM$_{2.5}$ and BC, centered on the IGP, CC, and NCP were supported by the reduction in anthropogenic activities (transportation, and industrial activities). The decrease in BC level can also be supported by media reports, and quoting data from industry survey that industrial production fell, with a − 25.61% (China) and − 33.21% (IGP) fall in coal consumption by mega power plants, since the lockdown period. Thus, indirectly increases the oxidizing capacity of the lower atmosphere, increases O$_3$, as discussed in Section 3. However, accurate estimates in the aerosols, PM$_{2.5}$ and BC are difficult due to their

![Fig. 10. Same as in Fig. 2, but for the tropospheric column NO$_2$ measured by OMI.](image)
longer atmospheric lifetime in the troposphere and mix complex behavior. From a global perspective, the decline rate in air pollutants appears to be higher in urban and industrial areas than the relatively clean remote areas (Carbon Brief, 2020; Kerimray et al., 2020; Kanniah et al., 2020). As highlighted earlier (section 3), the decline rate (NO₂, CO, and SO₂) in urban regions such as CC, PRL, and IGP are much higher than in clean areas (TP, NCP), comparatively. Kanniah et al. (2020) also analyzed local data from different regions (Manila, Bangkok, Kuala Lumpur, and Singapore) in Southeast Asia, to assess the impact of regional lockdown on air quality. The authors revealed a decrease in PM₁₀ (26–31%), PM₂.₅ (23–32%), NO₂ (63–64%), SO₂ (7–20%) and CO (25 to 30%) in the urban areas during the lockdown period are less compared to our findings for some pollutants, but well matched with the total column Ozone and AOT observed in the IGP and Chinese regions. However, the study is not accounted for all the possible mechanisms that could also partially account for the observed reductions in pollutant concentrations.

6. Conclusions

The present paper utilizes the multi-satellite information to understand and investigate the relative changes in column aerosols (AOT), particulate matter (PM₂.₅), and trace gases (CO, SO₂, NO₂, and O₃) concentrations during the DLD and PLD periods over the urban regions in South Asia. The major findings and outcomes of the study are summarized below.

1. The column AOT retrieved from the MODIS–Aqua was found lower than the normal values in the most polluted regions of IGP (0.53 ± 0.13) and CC (0.30 ± 0.30) attributed to the COVID-19 lockdown measures on a local and regional scale.
2. The sharp decrease in NO₂ for the DLD phase, in turn, enhances the ozone concentration that generally promoted the photochemical oxidation of biogenic organic and secondary pollutants present in the atmosphere.
3. Compared with the PLD phase, local pollution was accumulated despite a large reduction in air pollution emissions during the DLD period in the PRD region.
4. Quantitatively, the daily mean O₃ concentrations were enhanced by 5.66%–8.70% over the densely populated and urban background areas with a maximum in IGP (8.39%) and low (5.66%) in TP areas.
5. A significant decrease in PM₂.₅, BC/CO concentrations were recorded almost 25%–40% lower during the DLD period. This supports the fact that apart from other factors (natural/anthropogenic sources), the regional lockdown had a significant positive effect (decrease in aerosol) on the air quality of South Asia.

The present work is important and gives confidence to the regulatory bodies to implement mitigation measures and policymaking in future long-term air quality assessment on a local/regional basis. The same can be achieved through natural simulation and modeling techniques that will help to bring suitable alternatives for turning down anthropogenic activities.

Author statement

All authors have read and agreed to the published version of the manuscript. R.K. has taken part in methodology, formal analysis, visualization, investigation, and writing-original draft. K.R.K. contributed to conceptualization, data curation, resources, supervision, and writing and review-editing. T.Z. has contributed to supervision, project administration, funding, and writing & review-editing.

Data availability

Satellite (AIRS, OMI, and MODIS), and model reanalysis (MERRA-2) datasets are freely accessible to the public from the following websites https://modis.gsfc.nasa.gov/ & https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/

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Declaration of Competing Interest

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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