The Impact of Lockdown on Air Quality in Pakistan during the COVID-19 Pandemic Inferred from the Multi-sensor Remote Sensed Data

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ABSTRACT

The present study utilized multi-sensory gridded and reanalysis data in conjunction with the meteorological variables to evaluate the impact of lockdown due to the Coronavirus disease of 2019 (COVID-19) pandemic on the changes of concentration of atmospheric pollutants in Pakistan. We focused on assessing the significant changes of pollutant concentrations during March–May for the years 2019 and 2020 utilizing the satellite datasets observed from the Moderate Resolution Imaging Spectroradiometer (MODIS), Ozone Monitoring Instrument (OMI), Atmospheric Infrared Sounder (AIRS), and Modern-Era Retrospective analysis for Research and Applications (MERRA-2) reanalysis data. Low pollution levels were observed throughout the COVID-19 (March 25–May 31, 2020) compared to a similar period in 2019. The association of meteorology with air pollutants found that the periods of enhanced temperature and relative humidity likely contributed to a cleaner environment over the Indus Basin Region (IBR) and Balochistan Plateau (BP). The decrease in the mean planetary boundary layer Sulphur dioxide (SO₂) during the lockdown period of 2020 (DLP-2020) was evident by –36% in BP, –34% in Khyber Pakhtunkhwa (KPK), and –15.15% in IBR when compared to before the lockdown period of 2019 (BLP-2019). This is attributed to the limited transportation and control action plans of industrial activities including combustion sources taken by the Government of Pakistan for the DLP-2020 phase. During DLP-2020, a variable and least significant decline in surface particulate matter of size 2.5 μm (PM_{2.5}) concentration was observed in the urban regions of KPK (–19.17%) followed by IBR (–0.82%) and BP (–0.26%). Overall, a considerable reductions in Carbon monoxide (CO) and black carbon (BC) concentrations were smaller in rural and suburban areas of BP (–3.61%, –8.57%) followed by KPK (–0.79%, –11.39%) and IBR (–3.30%, –11.39%), respectively. This is due to the reduction in local emissions related to the lockdown measures taken in the control of pandemic. However, the ozone (O₃) concentrations witnessed an increase to a lower extent as 11.39%, 5.78%, and 4.74% in KPK, BP, and IBR, respectively attributed to rising in solar radiation intensity and temperature in hot summers, and decrease in NO_x levels during the study period.

Keywords: Air quality, Atmospheric pollutants, COVID-19, Pakistan

1 INTRODUCTION

The abrupt outbreak of the Coronavirus disease of 2019 (COVID-19) pandemic produced unprecedented societal impacts over the globe, in particular, the Asia continent, and has drawn

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considerable attention in the recent days and months. Since the detection of the realm's first case in China in late December 2019 and onward in January 2020 in the Asian continent, the concerned Governments of different countries have decided to declare a state of a health emergency. Hence, the regional areas were started locked-down on 23 January 2020, in Wuhan, Hubei province of China, and consequently followed the guidelines given by the World Health Organization (WHO, 2020a, b) to undergo lockdown in other nations. This has been referred to as the largest attempted home quarantine in human history around the world, includes Pakistan (South Asia) with the nation-wide lockdown from 25 March 2020 onwards in different phases. Responding to the ongoing outbreak, the majority of industrial and commercial activities including regional to and from transportation was stopped for about three weeks at an early stage in China. While, the similar sanitary state of emergency was extended to almost all the regions of Asia, which later on spread to the whole world (NASA, 2020).

At the time of completion of writing this manuscript (as of 15 December 2020) a total of 73.99 million cases of COVID-19 had been detected and confirmed across the globe, among which, Pakistan shares more than 0.85 million (World Health Organization., 2020a, 2020b), with 54448 registered cases in Khyber Pakhtunkhwa (KPK) province, 130706 in the Indus Basin Region (IBR), and 17880 COVID-19 positive cases in the Balochistan Plateau (BP). 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 of Asian countries including Pakistan (Alam *et al.*, 2012; Khan *et al.*, 2019, 2020), China (Shen *et al.*, 2020; Xu *et al.*, 2020), India (Sharma *et al.*, 2020; Venkat Ratnam *et al.*, 2021) and others. Owing to the pandemic lockdown, regular social activities and the oil/energy consumption of each region has been undoubtedly mitigated emphatically. Several studies over different regions of Asia (Ahmadi *et al.*, 2020; Jahangiri *et al.*, 2020; Kerimray *et al.*, 2020; Sharma *et al.*, 2020; Venkat Ratnam *et al.*, 2021), China (Bao and Zhang, 2020; Muhammad *et al.*, 2020; Shen *et al.*, 2020; Xu *et al.*, 2020), Middle East (Broomandi *et al.*, 2020; Faridi *et al.*, 2020), Europe (Bauwens *et al.*, 2020; Martínez *et al.*, 2020; Nakada *et al.*, 2020; Siciliano *et al.*, 2020; Tobías *et al.*, 2020; Sannino *et al.*, 2021), and USA (Bauwens *et al.*, 2020; Berman and Ebisu, 2020; CDC, 2020) had examined and documented the significant role of regional lockdown on air quality by using the ground- and space-based sensors. However, it is still needed to assess the atmospheric pollution influence during the regional lockdown in different domains of Asia, including Pakistan to reveal its implication for pollution control strategies. The NASA satellite images clearly showed that the concentrations of trace gases dropped drastically (30–40%) in February over Wuhan (NASA, 2020; Wang *et al.*, 2020). Both the air precursors will improve the air quality on a local and regional basis ((Bao and Zhang, 2020).

According to the investigation of the NASA scientists (NASA, 2020), the pollutant levels (such as Carbon monoxide (CO), Carbon dioxide (CO₂), and Black Carbon (BC)) in the air is decreased significantly by –30% for the trace gases, and –25% for CO₂ in central China, and –6% in the world (Carbon Brief, 2020) after the first lockdown in China. Further, a decrease in pollutant levels over North China was found by an average of –13.71%, –5.91%, –6.82%, and –4.60%, for particulate matter with the aerodynamic size of 10 µm and 2.5 µm (PM₁₀ and PM_{2.5}), Sulphur dioxide (SO₂), and carbon monoxide (CO) over 44 different cities reported by Bao and Zhang (2020) using the remote sensing data. However, in another work conducted in India, the decrease in PM_{2.5} concentration was found the highest (–50%) over New Delhi (India) out of several major cities in the Asian continent during the COVID-19 lockdown period (Mahato *et al.*, 2020). Later on, by using the same resources (remote sensing data), a significant decline in the concentrations of basic air pollutants PM₁₀ (43%), PM_{2.5} (31%), NO₂ (18%), and CO (10%) was observed over 22 major cities of India during the first phase of lockdown period (26 March–14 April 2020) (Sharma *et al.*, 2020). Moreover, they have reported that the surface ozone (O₃) levels are gradually exceeded in almost all the study sites in India ranging from 5% to 22.5%. Further, Panda *et al.* (2020) and Chauhan and Singh (2020) found a decrease in PM₁₀ (60%), PM_{2.5} (36%), and CO (30.4%) concentrations using the in situ measurements in India for the study period (January–February 2020).

A similar decrease is also seen in other trace gases resulted in the improvement of regional air quality over many countries that remain under lockdown. Using the ground- and satellite-based measurements, a striking reduction in air pollutants SO₂, CO, and PM_{2.5} have been observed over India (–17.97%, –10%, and –43%), Barcelona (–19.4%, –28%), Germany, Belgium (–20%), and U.S.A (–20 to 38%) (Bauwens *et al.*, 2020; Dantas *et al.*, 2020; Li *et al.*, 2020; Panda *et al.*, 2020;

Tobías *et al.*, 2020). However, in Western Europe (Rome and Turin), the reduction in some pollutants ($PM_{2.5}$ and PM_{10}) was recorded to be relatively lower (-10.21%). All these studies have examined and documented the significant role of regional lockdown on air quality by using ground and space-borne observations. However, it is needed to assess the atmospheric impacts of pandemic outbreaks in the unexplored South Asia region, particularly in Pakistan to reveal its implication for pollution control strategies. Hence, the present work elucidates the effectiveness of present lockdown measures on the air quality in different regions of Pakistan, namely Khyber Pakhtunkhwa (KPK), Indus Basin Region (IBR), and Balochistan Plateau (BP). In this regard, the space-borne satellites (Moderate Resolution Imaging Spectroradiometer (MODIS), Ozone Monitoring Instrument (OMI), and Atmospheric Infrared Sounder (AIRS) and Modern-Era Retrospective analysis for Research and Applications of version 2.0 (MERRA-2) reanalysis model data set have been executed on the selected regions located in the study domain to ascertain the significant aftermath of Before Pandemic Lockdown Period (BLP) and During pandemic Lockdown Periods (DLP) of COVID-19. In this study, we have analyzed the spatiotemporal distributions of precursor gases (SO_2 , CO , O_3), BC, $PM_{2.5}$, and column aerosol optical thickness (AOT) to interpret and understand the reasons behind the significant changes in regional air quality under the lockdown period in Pakistan.

2. STUDY DOMAIN

The present study evaluates the variations of main atmospheric pollutants concentrations over Pakistan (latitude from 24° to $37^\circ N$, and longitude between 62° and $75^\circ E$). The mainland is presented with high topographical heterogeneity (see Fig. 1), varying aerosol emission sources, and distinct meteorological properties. The area is marked by large variations in temperature across different seasons, with a mean from $2.3^\circ C$ in winter to about $36^\circ C$ in summer. The rapidly expanding urbanization, industrial/agricultural activities, and energy utilization resulted in increasing amounts of anthropogenic emissions and, in turn, deterioration of air quality (Alam *et al.*, 2012). In the present study, to analyze the impact of COVID-19 pandemic lockdown on the air

Fig. 1. Topographic map of Pakistan with a color scale presented at bottom left to the figure. The areas enclosed in pink box represent major regions considered in the present study from the entire domain.

quality, the study domain (Pakistan) is divided into three major regions as Khyber Pakhtunkhwa (KPK), Indus Basin Region (IBR), and Balochistan Plateau (BP). The KPK region is one of the urban and populated regions of the country, bounded by the greater Himalayan mountain range on one side, which acts as a barrier, trapping the aerosols and air pollutants over the region. The IBR has the highest population density in Pakistan and is characterized by large emission sources and pollutants including desert dust and anthropogenic aerosols from the industrial sectors. The BP region is mostly known for high elevation mountainous regions and reflects the semi-urban and rural environment of the study domain, where anthropogenic activities are observed less compared to the rest of the study areas (Zhang *et al.*, 2020). However, being the land lock region, the air pollutants mostly staying for a longer period, throughout the year in this region. In recent years, with the increase in population, rapid urbanization in most of the areas resulted in an enhanced amount of the consumption of fossil fuel in the energy production sectors, while the biomass burning in the rural areas has to lead to high aerosol loading over Pakistan (Alam *et al.*, 2012).

2.1 Satellite and Reanalysis Data

The data used in this study are observed from three Earth Observation System (EOS) satellites namely, Moderate-resolution Imaging Spectroradiometer (MODIS), Atmospheric Infrared Sounder (AIRS), and Ozone Monitoring Instrument (OMI), and also the MERRA-2 reanalysis model data for the study period. The datasets from the above sensors were downloaded for a period of a total of 68 days (~9 weeks) Before- and During- the Lockdown periods labeled as BLP-2019 (March 25–May 31, 2019) and DLP-2020 (March 25–May 31, 2020), respectively. The retrieved satellite data were further processed using different computational tools such as GEE (Google Earth Engine), CCP (Cloud Computing Platform), Arc GIS, and MatLab probably the best proposition to understand the changes in air pollutants; and to evaluate the impact of lockdown on regional air quality over the study domain.

2.1.1 The AIRS sensor

The AIRS launched on 4 May 2002 (onboard NASA's Aqua platform) is capable to globally monitor the tropospheric CO mole fraction (in ppbv; parts per billion volume) in the air (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 1650 km swath (Aumann *et al.*, 2003). The sensor provides broad spectral coverage in the range of 3.75 to 15.4 μm with 2378 different channels. Further, the AIRS enable 70% of the global retrieval twice per day, nearly in both hemispheres with an angle range of 45°–80°. The AIRS data sets are validated using the ground-based total column CO observations measured in Russia and Australia; and agreement between AIRS and air-borne measurements were found within an average of 10–15 ppbv (Yurganov *et al.*, 2008). This agreement between the space-borne AIRS and ground-based total column measurements (CO) (not shown here) enables us to use AIRS in the present work to investigate the spatial and temporal levels of CO for the phases of BLP-2019 and DLP-2020.

2.1.2 The MODIS sensor

The global imaging sensor MODIS 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 (Kaufman *et al.*, 1997). The sensor measures radiances at spatial resolutions of 0.25, 0.5, and 1.0 km, depending mainly on the waveband. The aerosol products derived from MODIS have proven to be reliable over oceans, dark and bright land surfaces after recent improvements in the aerosol retrieval algorithms (Sayer *et al.*, 2013). Over dark surfaces (vegetative land and oceans), AOT is retrieved using the Dark-Target (DT) algorithm (Kaufman *et al.*, 1997). However, the Deep Blue (DB) algorithm is used for bright surfaces (Hsu *et al.*, 2004). The complete details about DT and DB algorithms can be found in Levy *et al.* (2013). In this study, daily mean AOT is obtained from archived MODIS recent Collection 6.1 (MOD08) Level 3 Aqua (merged DT and DB) dataset. The Level 3 product is the new version of MODIS Level 2 with the best quality assurance (QA) flag (value-3) and is available at spatial resolution of $1^\circ \times 1^\circ$ (Kaufman *et al.*, 1997). The QA data files are extracted using the HDF view tool. The radiometric calibration and orbit stability both are rigorously maintained by the MODIS

Characterization Support Team (MCST), to within $\pm 2\text{--}3\%$ at specific situations (Remer *et al.*, 2005). Also, through this QA/QC Check, data quality and uniformity have improved substantially over the last couple of years. However, Global validation exercises have indicated expected uncertainties for AOT₅₅₀ as $\pm (0.05 \times \text{AOT} + 0.03)$ and $\pm (0.15 \times \text{AOT} + 0.05)$ over ocean and land, respectively (Kaufman *et al.*, 1997; Remer *et al.*, 2005).

2.1.3 The OMI sensor

The OMI Aura is a nadir-viewing spectrometer onboard NASA's Aura satellite and is the first sensor capable of working on UV and visible spectrum with a charge-coupled device, enabling daily global monitoring of O₃, NO₂, and SO₂ concentrations (Levelt *et al.*, 2006). In addition to AIRS and MODIS, OMI Aura derived daily total column O₃ and SO₂ observed in the planetary boundary layer (PBL) were analyzed in the present work. The OMI sensor utilizes two algorithms for retrieving aerosol information from the measurements of TOA reflectance: i) the OMAERUV aerosol product (near-UV algorithm) and ii) OMAERO aerosol product (multi-wavelength algorithm) (Torres *et al.*, 1998). The precision uncertainty for the derived gridded O₃ is 5 Dobson Unit (DU) with a mean offset of 2 DU (OMI/MLS) (Ziemke *et al.*, 2009). Column amount SO₂ in the PBL has an uncertainty of 0.5–0.9 DU (Theys *et al.*, 2015). The discrepancies are even smaller on a regional scale and when considering individual sectors. Further, the OMI retrieved O₃ and SO₂ data are available from the NASA GES DISC at <http://disc.gsfc.nasa.gov/>.

2.1.4 The MERRA-2 reanalysis data

The Modern-Era Retrospective analysis for Research and Applications (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 1980 to the present. The model uses the 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 $0.5^\circ \times 0.625^\circ$ at 72 pressure levels (from the surface to 0.01 hPa) with both instantaneous and time-averaged (hour, 3-hours, and month). 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 and meteorological fields, accounting for their interaction through the radiative effects of atmospheric aerosol (Gelaro *et al.*, 2017). However, the aerosol assimilation system in MERRA-2 uses AOT measurements from satellite instruments (such as MODIS, MISR, AVHRR) and also from the ground-based Aerosol Robotic Network (AERONET) stations. The MERRA-2 surface mass concentration of hourly BC and column mass density of PM_{2.5} were analyzed in the present work, which is in open access and free for the public (<https://disc.sci.gsfc.nasa.gov/>). Till now, the uncertainty in MERRA-2 derived PM_{2.5} (compared to ground data set) is revealed as 19.2–23.6% in Asia (China) (Ma *et al.*, 2020a). The underestimations in PM_{2.5} concentration by MERRA-2 is affiliated mainly with the uncertainty in the magnitude of the emission inventory used in the comparison model. An overview of the MERRA-2 modeling system and a more detailed description of aerosols in the MERRA-2 database can be found in Buchard *et al.* (2017), Gelaro *et al.* (2017), and Randles *et al.* (2017).

3 RESULTS

3.1 Changes in Aerosol and Trace Gases Concentrations

In this study, we used the column AOT from the MODIS-Aqua satellite, CO mole fraction from the AIRS sensor, SO₂ in the PBL and total column O₃ from the OMI satellite along with the mass concentrations of PM_{2.5} and BC from the MERRA-2 reanalysis model observed over three different regions (KPK, IBR, and BP) in Pakistan. It is taken to measure the variations of atmospheric pollutant concentrations because of the general nation-wide COVID-19 lockdown in Pakistan. We first analyzed the satellite-derived estimates of averaged AOT, PM_{2.5}, SO₂, CO, BC, and O₃ concentrations across the selected regions of interest for the BLP-2019 and DLP-2020 (Figs. 2, 3, and Table 1). The MODIS-Aqua satellite and MERRA-2 reanalysis model estimates showed a significant decline in column AOT and surface PM_{2.5} by -0.02 (-9.09%) and $-3.7 \mu\text{g m}^{-3}$ (-19.17%) across KPK, -0.02 (-4.34%) and $-0.3 \mu\text{g m}^{-3}$ (-0.82%) in the IBR, and -0.01 (-2.9%) and $-0.1 \mu\text{g m}^{-3}$ (-0.26%),

Fig. 2. Changes in columnar AOT₅₅₀ retrieved from the MODIS-Aqua (upper panels); column amount of SO₂ in the PBL from OMI (middle panels); and mole fraction of CO in air from AIRS (bottom panels) around Khyber Pakhtunkhwa, Indus Basin Region, and Balochistan Plateau: (a) Before-(BLP-2019), (b) During-(DLP-2020) the lockdown period, and (c) the fractional change (% difference) between (a) and (b) calculated in unit of ppbv (CO); DU (SO₂); and AOT (unit less). 1 Dobson Unit (DB) = 0.4462 mmol m⁻² and ppbv = parts-per billion volume.

respectively in the BP region during the study period influenced by the traffic emission and biogenic sources in addition to the contribution from the anthropogenic sources (Alam *et al.*, 2012).

The CO concentrations were also found lower during the DLP-2020 in comparison to last year (PLP-2019) for the BP region -3.98 (-3.61%) ppbv followed by IBR with -3.92 (-3.30%) ppbv. No significant lower values of concentrations were recorded for KPK -0.94 (-0.79%) ppbv during the study period (Fig. 2, Table1). The decrease in CO levels is likely related to the temporary augmented control in local/regional pollution activities during the lockdown period. On the contrary, a more

Fig. 3. Same as in Fig. 2, but for the PM_{2.5} (upper panels), O₃ from the OMI (middle panels), and mass concentration of BC (bottom panels) from MERRA-2 for the study period.

pronounced decline in SO₂ was found as –36% for BP followed by KPK (–34%) and comparatively lower for IBR (–15.15%). The same is attributed to the alteration of basic source activities, primarily associated with the restriction of transportation and controlled industrial activities. Further, the gradual increase in O₃ concentrations is visible clearly from the spatial plot (Fig. 3(b), Table 1) during the DLP-2020, with a mean ($\pm$ SD) and gradual percent increase of 287.79 ± 13.57 DU and 5.78% in the BP region followed by the IBR with 300.65 ± 14.66 DU and 4.63%, and KPK with 304.32 ± 19.38 DU and a comparatively lower increase in O₃ of 4.05%. The gradual increase in O₃ is associated with the decreasing shift in primary pollutant NO_x and PM_x ($x = 2.5$ or $10 \mu\text{m}$) generated from the urbanized and industrialized areas of Pakistan. Another potential reason is the insolation and temperature shift from spring to summer in the northern hemisphere led to an increase in O₃ (Mahato *et al.*, 2020).

Table 1. Basic statistics pertaining to 24 h mean ($\pm$ SD) concentrations of AOT₅₅₀, PM_{2.5}, BC, and trace gas pollutants (SO₂, CO, O₃ and NO₂) for the period between March 25 to May 31, 2020 (during the lockdown period (DLP-2020) and before the lockdown period (BLP-2019)) for the three major study regions Khyber Pakhtukhwa, Upper Indus Basin and Balochistan Plateau in Pakistan. The Difference of two different data periods with its percentage values is also presented.

Study Site	Air Pollutant (Unit)	BLP-2019	DLP-2020	Difference	% Variation
Khyber Pakhtunkhwa	AOT ₅₅₀	0.22 $\pm$ 0.03	0.19 $\pm$ 0.04	−0.02	−9.09
	PM _{2.5} ($\mu\text{g m}^{-3}$)	29.3 $\pm$ 2.4	25.6 $\pm$ 3.9	−3.7	−19.17
	SO ₂ (DU)	0.05 $\pm$ 0.06	0.033 $\pm$ 0.065	−0.017	−34
	CO (ppbv)	119.55 $\pm$ 1.13	118.60 $\pm$ 0.54	−0.94	−0.79
	O ₃ (DU)	292.23 $\pm$ 13.42	304.32 $\pm$ 19.38	12.08	4.13
	BC ($\mu\text{g m}^{-3}$)	0.79 $\pm$ 0.16	0.74 $\pm$ 0.1	−0.09	−11.39
Upper Indus basin	AOT ₅₅₀	0.46 $\pm$ 0.9	0.44 $\pm$ 0.00	−0.02	−4.34
	PM _{2.5} ($\mu\text{g m}^{-3}$)	36.7 $\pm$ 10.1	36.4 $\pm$ 1.4	−0.3	−0.82
	SO ₂ (DU)	0.066 $\pm$ 0.065	0.055 $\pm$ 0.03	−0.01	−15.15
	CO (ppbv)	118.71 $\pm$ 4.41	114.79 $\pm$ 4.2	−3.92	−3.3
	O ₃ (DU)	287.04 $\pm$ 13.48	300.65 $\pm$ 14.66	13.61	4.74
	BC ($\mu\text{g m}^{-3}$)	1.56 $\pm$ 0.19	1.21 $\pm$ 0.17	−0.35	−22.43
Balochistan Plateau	AOT ₅₅₀	0.35 $\pm$ 0.01	0.34 $\pm$ 0.03	−0.01	−2.9
	PM _{2.5} ($\mu\text{g m}^{-3}$)	38.8 $\pm$ 2.5	38.7 $\pm$ 4.2	−0.1	−0.26
	SO ₂ (DU)	0.05 $\pm$ 0.06	0.032 $\pm$ 0.06	−0.018	−36
	CO (ppbv)	110.06 $\pm$ 1.85	106.08 $\pm$ 2.54	−3.98	−3.61
	O ₃ (DU)	272.05 $\pm$ 11.73	287.79 $\pm$ 13.57	15.74	5.78
	BC ($\mu\text{g m}^{-3}$)	0.35 $\pm$ 0.10	0.31 $\pm$ 0.06	−0.03	−8.57

The magnitude of decrease in BC, for the suburban and industrial background regions of IBR and KPK, was found higher (−22.43% and −11.39%) with a mean difference of $-0.35 \mu\text{g m}^{-3}$ and $-0.03 \mu\text{g m}^{-3}$, respectively. Notable reductions are also seen in industrial, suburban, and rural sites across the country (Fig. 3). However, PM_{2.5} concentration has counted the least in comparison to other air pollutants for almost all the study areas. It is known that PM_{2.5} aerosols are mainly associated with the combustion of coal and natural gas, power plants, industries, and automobiles. Indeed, the lockdown measures reduced the outdoor emission activities but on the other hand, it was replaced by the indoor domestic heating and relevant biomass burning resources at the same time in DLP-2020. The reason behind this is the sources (particles from residential energy, agriculture sector, including desert dust) affiliated with the emission of PM_x, which were observed partially active in the study areas. Further, the meteorological parameters such as precipitation, relative humidity, and wind speed are also considered to be active parameters in this domain that might be interlinked with the preset results (Khan *et al.*, 2020).

Overall, the study domain (Pakistan) showed a more substantial decrement in the surface mass concentration of BC in the DLP-2020, with the mean statistical variance (% Diff) of -0.10 (−13%) $\mu\text{g m}^{-3}$ followed by PM_{2.5} with -2.25 (−7.39%) $\mu\text{g m}^{-3}$, SO₂ with -0.01 (−2.24%) DU and CO -5.55 (−4.76%) ppbv in comparison to the last year (Figs. 2, 3, and 4). Since, the air pollutants such as Nitrates and Sulfates are emitted from the urban and industrial areas by transportation units, thermal power plants, and other industrial activities. While the carbon-rich soot and PM_x are being produced by the burning of coal and wood, and consumption of fossil fuel. The burning of agricultural residues after harvest and charcoal used for cooking in the rural areas of BP produces smoke that contains black or organic carbon (although agricultural burning or biomass burning occurs more regularly) during this period every year (Mayol-Bracero *et al.*, 2002). The shift in AOT was observed overall with the mean statistical variance (% Diff) of -0.03 (−9.8%), and an increase in O₃ was noticed as 13.96 DU (4.83% DU) in Pakistan.

3.2 Role of Meteorology

The regional meteorology produces a unique experiment to assess the efficiency of air pollution diminution during the COVID-19 Pandemic period in Pakistan. Since meteorology always played an important role in the formation and transport of air pollutants in both urban and rural atmospheres

Fig. 4. Histogram maps presenting the averaged AOT₅₅₀, PM_{2.5}, and precursor gases (CO, BC, SO₂, O₃) concentrations observed from the MODIS-Aqua, MERRA-2, AIRS and OMI retrievals, respectively over industrial, urban, sub-urban and rural sites in Pakistan before and during the pandemic period 25 March–31 May for the years 2019 and 2020. Vertical bars correspond to one sigma standard deviation of the mean.

(Albrecht *et al.*, 1989; Lelieveld and Heintzenberg, 1992). We compared briefly, the meteorological parameters such as temperature (in K) and relative humidity (in %) with the aerosol and trace gas concentrations during DLP-2020 over the study areas (Figs. 5–7) in Pakistan.

Temperature is one of the key influencing factors for air pollutant concentrations across Pakistan (Khan *et al.*, 2019). Our observation shows an increase (decrease) in temperature (RH), (Figs. 5(a)–7(a)) for the DLP-2020 phase. The temperature rise is usually expected during these days (March–May) of the year in the study region (Alam *et al.*, 2012). Throughout the DLP-2020, the gradual increase in temperature is observed with noticeable periodic alteration in RH over the study areas, with maximum T (304K) in UIP followed by BP with 300 K and 299 K over the KPK region and lower RH values of 30%, 20%, and 37%, respectively. The most notable variation occurred over KPK, where the temperature dropped down almost three times with a visible difference of (274–296 K) during the first phase of DLP-2020 (Figs. 5(a)–5(f)) with an increase in RH. These results could promote reductions in aerosols. A gradual decline in AOT, CO, BC, and SO₂ during lockdown can also be seen in the temporal evaluation (Figs. 5–7). Results clearly show that a sharp decline in both AOT and PM_{2.5} values is observed during the first week of lockdown; however, after some time, (during the last week of DLP-2020) a sudden increment in both the parameters is noticed attributed to the end of lockdown phase and the regain in anthropogenic activities associated with the restoration of social and commercial pursuits and increase in temperature (Gunthe *et al.*, 2020; Ma *et al.*, 2020b). Since, relative humidity (RH) plays an effective role in the hygroscopic growth of atmospheric pollutants (Carrico *et al.*, 2003; Kumar *et al.*, 2013; Ahlawat *et al.*, 2020). Under humid conditions, the air pollutant exhibited a linear decrease with the temperature in the study regions (Figs. 5–7). In general, high temperature favors more air pollutants

Fig. 5. Variations of daily averaged temperature, relative humidity (RH) with (a) AOT_{550} , (b) Dust surface mass concentration of $PM_{2.5}$, (c) Planetary Boundary Layer SO_2 column amount, (d) Mole fraction of CO, (e) total column amount of O_3 , and (f) BC surface mass concentration in Khyber Pakhtunkhwa during March–May 2020.

to dispersion in a dry/less humid atmosphere and results in a lower concentration of aerosols. Results indicate that temperature is likely to have a substantial effect on the variations of atmospheric pollutant concentrations. It is predicted that a 10°C decrease in temperature would increase air pollutant yields by 20–150%, in presence of a humid atmosphere (Bowman *et al.*, 2001).

Total column ozone (O_3) concentrations typically experience a cycle opposite that of other trace gases, with peak levels at mid of the DLP-2020 in all study areas (Figs. 5–7). This is attributed to the result of a gradual decline in NO_3 (Table 1) and the potential increase in temperature beside the dry atmosphere. The daily mean column amounts of SO_2 levels in the PBL tend to be highly variable; however, in general, the cause factors are not well defined amidst the lockdown period. For comparison, the recent studies have investigated the changes of air quality under lockdown condition due to the COVID-19 at different regions of the globe (e.g., Jain and Sharma, 2020; Panda *et al.*, 2020; Sharma *et al.*, 2020; Shen *et al.*, 2020; Sannino *et al.*, 2021; Venkat Ratnam *et al.*, 2021). The results revealed and suggested that meteorology plays a key role in the variation of air pollutant levels on regional and global scales. Further, Putaud *et al.* (2004) and Jayamurugan *et al.* (2013) have statistically shown a strong inverse linkage between RH and air pollutant concentration with the emphases that 49.99% RH provides the more favorable condition to PM_{10} lead to a 1.09 times increase, and 20% RH contribute 1.07 times increase in $PM_{2.5}$ concentration. Therefore, along with the lockdown, the static meteorological conditions also played a significant role in the decrease of air pollutant levels in most of the places of South Asia including Pakistan, India, and around the world (Jayamurugan *et al.*, 2013; Ahmadi *et al.*, 2020; Gunthe *et al.*, 2020; Shen *et al.*, 2020; Sannino *et al.*, 2021; Venkat Ratnam *et al.*, 2021).

Fig. 6. Same as in Fig. 5, but for the Upper Indus Basin Region.

4 DISCUSSION

From the obtained results, we could note that the government has taken initial measures in response to the COVID-19 pandemic that has positively impacted the air quality in different urban and industrial regions of the country. The aerosol (AOT, BC, PM_x) and trace gases (NO_2 , SO_2 , O_3 , CO) concentration were reduced in most of the study domain during the DLP-2020. The IBR and the surrounding regions showed a marginal to lower decrease in the spatial and temporal extent, despite reports of greatly reduced anthropogenic activities (industrial, transportation) during the DLP-2020 period. Besides, the increase in O_3 across the country during the lockdown phase observed by Aura-OMI suggests that vehicular and traffic measures may have little effect in controlling regional air pollution. Because the concentration of the studied pollutant was not observed as low as was expecting, which is mainly associated with the domestic activities and the seasonal production of natural dust particles actively visiting the study region every year in summer and early spring. Regional meteorology is also playing an active role in the increase of O_3 .

Dealing with the impact of COVID-19 pandemic lockdown on air quality, several studies were conducted and published during the last few months, by utilizing the space-borne and ground-based data sets around the globe (e.g., Berman and Ebisu, 2020; Dantas *et al.*, 2020; IQAIR, 2020; Mahato *et al.*, 2020; nCoV-2019 Data Working Group, 2020; Tobias *et al.*, 2020; WHO, 2020a, b) and in Asian continent (e.g., Abdullah *et al.*, 2020; Chen *et al.*, 2020; Li *et al.*, 2020; Muhammad *et al.*, 2020; Sharma *et al.*, 2020; Wang *et al.*, 2020; and references therein). Almost all of these studies showed declining tendencies in trace gases (NO_2 , SO_2 , O_3 , CO, BC), column aerosol loading, and PM_x concentrations. The reasons for the considerable decrement in pollutant levels are

Fig. 7. Same as in Fig. 5, but for the Balochistan Plateau.

related to the specific features of location, relative influence of natural/anthropogenic emission, local/regional meteorology, and the proximity of different energy sectors.

For instance, the Ministry of ecology and environment of China (MEEC, 2020) predicted a gradual decrease in other air pollutants by -20% , -15% , and -21% in PM_{10} , $PM_{2.5}$, and SO_2 , respectively (Wang *et al.*, 2020) during the lockdown period of January–February 2020. A large decrease in BC (-45.4%) and PM_{10} (-31%) was observed in the urban regions of Europe such as Barcelona (Spain) (Tobías *et al.*, 2020) and Milan (Italy) (Conticini *et al.*, 2020). This agrees well with the percent decrease of CO and BC pollutants over IBR and BP regions in Pakistan. Recent studies have also included the analysis of O_3 , a highly variable and secondary aerosol species, mainly dependent on the meteorological factor (solar radiation and temperature) and the varying season. The daily O_3 levels are significantly increased in New Delhi, India (17%), North China (14 – 45%), Morocco (12 – 33%), and Spain (29 – 58%), which is far greater than from our results. However, in general, the changes in O_3 are mostly associated or linked up with the variations in NO_x (Reddy *et al.*, 2012). Hence, as the NO_2 decreases result in an increase of O_3 and vice versa (Kerimray *et al.*, 2020). A more detailed analysis and comparison of different studies are given in Table 2.

5 CONCLUSIONS

The present study provides a preliminary evaluation of improvements in the regional air quality of Pakistan during the COVID-19 pandemic nationwide lockdown. We observed pronounced changes (in percent) detected by the satellite-derived estimates in surface mass concentrations of BC, $PM_{2.5}$, and column SO_2 as -11.39% , -19.17% , and -34% over the KPK region; -8.57% , -0.26% ,

Table 2. Mean concentrations of CO, O₃, SO₂, BC, and PM_{2.5}, analyzed for the BLP-2019 and DLP-2020 phases over different regions across the globe. The differences of two different data periods with its percentage values are also presented.

Air pollutants	Study Region	BLP-2019	DLP-2020	Relative Difference (%)	Citation
CO (ppbv)	Delhi (India)	1.03	0.72	−30.35	Mahato <i>et al.</i> (2020)
	Kolkata (India)	0.6	0.5	−18.18	Jain and Sharma (2020)
	Hubei (China)	1.207	1.02	−16.79	Bao and Zhang (2020)
	Urban location (Malaysia)	0.8	0.49	−48.06	Kanniah <i>et al.</i> (2020)
	Chennai (India)	0.79	0.52	−41.22	Jain and Sharma (2020)
O ₃ (DU)	Delhi (India)	34.05	34.32	0.79	Mahato <i>et al.</i> (2020)
	Bhubaneswar (India)	34.7	22.2	−36.15	Panda <i>et al.</i> (2020)
	Kolkata (India)	45.55	40.11	12.70	Jain and Sharma (2020)
	Wuhan (China)	35.33	79.22	76.63	Lian <i>et al.</i> (2020)
	Urban location (Malaysia)	22	23.99	8.65	Kanniah <i>et al.</i> (2020)
SO ₂ (DU)	Chennai (India)	44.1	45.2	2.46	Jain and Sharma (2020)
	Sale (Morocco)	6.6	3.3	−0.49	Otmani <i>et al.</i> (2020)
	Urban location (Malaysia)	1.42	0.99	−35.68	Kanniah <i>et al.</i> (2020)
SO ₂ (μg m ^{−3})	Hubei (China)	15.81	13.83	−13.36	Bao and Zhang (2020)
BC (μg m ^{−3})	Bhubaneswar (India)	1.94	0.95	−51.03	Panda <i>et al.</i> (2020)
PM _{2.5} (μg m ^{−3})	Delhi (India)	80.51	37.75	−53.11	Mahato <i>et al.</i> (2020)
	Sao Paulo (Brazil)	12.9	12.5	−3.60	Nakada <i>et al.</i> (2020)
	Chennai (India)	29.38	27.33	−7.23	Jain and Sharma (2020)
	Hubei (China)	81.83	65.81	−21.70	Bao and Zhang (2020)
	Wuhan (China)	65.5	40.11	−48.08	Lian <i>et al.</i> (2020)
	Urban location (Malaysia)	32.3	22.34	−36.46	Kanniah <i>et al.</i> (2020)

and −36.1% over the BP region, respectively during DLP-2020 and BLP-2019 periods. However, the decline in the levels of BC (−22.43%), PM_{2.5} (−0.82%), and SO₂ (−15.15%) was found comparatively variant in the region of IBR. Despite, the visible decrease in the air pollutant concentrations, some of them (PM, CO) was found remains less elevated in many regions of Pakistan. As expected, a significant decrease in column aerosol load was observed over KPK, IBR, and BP with a difference (% variation) of −0.02 (−9.09%), −0.02 (−4.34%), and −0.01 (−2.9%), respectively. Among all pollutants, a slight increase in O₃ was found in BP (5.78%), IBR (4.74%), and KPK (4.13%) for the DLP-2020. In summary, a considerable reduction in the pollutant concentrations of AOT, BC, CO, PM_{2.5}, and SO₂ over different regions in Pakistan attributed to the implementation of COVID-19 pandemic lockdown. When comparing DLP-2020 to the same period in BLP-2019, we found important differences in surface temperature and RH that could strongly influence air pollutant levels in Pakistan. It was found that these meteorological factors provided a more favorable environment for the decrease in pollutant concentrations in DLP-2020 compared to BLP-2019. The present work is important and gives confidence to the regulatory bodies to implement mitigation measures in future long-term air quality assessment on a local/regional basis. The same can be achieved through a natural simulation and modeling techniques that will help to bring suitable alternatives for turning down the anthropogenic activities.

ADDITIONAL INFORMATION

CRedit Author Statement

All authors have read and agreed to the published version of the manuscript.

Rehana Khan: Data curation, Methodology, Formal analysis, Visualization, Investigation, Writing-Original Draft. Kanike Raghavendra Kumar: Conceptualization, Resources, Supervision, and Writing-review and editing. Tianliang Zhao: Project Administration, Supervision, and Writing-review and editing.

Conflicts of Interest

The authors declare that they have no competing financial interests or personal relationships

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Data Availability Statement

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

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