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Improved air quality during COVID-19 at an urban megacity over the Indo-Gangetic Basin: From stringent to relaxed lockdown phases

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A R T I C L E I N F O

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A B S T R A C T

The enforced lockdown amid COVID-19 pandemic eased anthropogenic activities across India. The satellite-derived aerosol optical depth (AOD) and absorption AOD showed a significant reduction of ~30% over the Indo-Gangetic Basin (IGB) in north India during the lockdown period in 2020 with respect to the previous year 2019, when no such lockdown was in effect. Further, near-surface air pollutants were investigated at an urban megacity Delhi during 01 March to 31 May 2020. Except O_3, a drastic reduction in PM_{10}, $PM_{2.5}$, NO, NO_2 and CO concentrations were observed by ~58%, 47%, 76%, 68% and 58%, respectively during the lockdown period of 2020 as compared to 2019. While, O_3 was low in the initial phase and gradually increased with progression of lockdown phases, the mean O_3 during the entire lockdown period was nearly similar in both the years. Though, all the measured pollutants showed significant reduction during the entire lockdown, a phase-wise enhancement, associated with the conditional relaxations was observed in their concentrations. Thus, the present results may help, not only to assess the impact of outbreak on air quality, but also in designing the mitigation policies in urban megacities in more efficient ways to combat the air pollution problems.

1. Introduction

The Indian subcontinent is the home to about 18% inhabitants of the global population and greatly vulnerable to air pollution, especially the Indo-Gangetic Basin (IGB). IGB has been identified as one of the global pollution hotspots of particulate matter of diameter smaller than 2.5 μm ($PM_{2.5}$) (Upadhyaya et al., 2018; Ojha et al., 2020). In addition to particulate matters, nitrogen dioxide (NO_2) and sulphur dioxide (SO_2) are among the most watched gaseous ambient air pollutants, which found to regularly exceed to their national ambient air quality standards (Wu, 2012). Air pollution shown to have harmful effects on human health associated with respiratory and cardiovascular diseases and mortality (Cohen et al., 2017; Chowdhury et al., 2018).

Delhi, the capital city of India, is an urban megacity situated in the northwest IGB region. The city has been listed as one of the top-

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most polluted cities in the world (WHO, 2016; Khanna and Sharma, 2020). The major anthropogenic activities in Delhi include vehicular exhaust, industrial emissions, residential pollution, and solid waste/biomass burning, which results in severe-to-worst air quality in the post-monsoon and early winter seasons (Sahu et al., 2015; Kishore et al., 2019; Bikkina et al., 2019; Kanawade et al., 2020; Kulkarni et al., 2020; Tobler et al., 2020). The $PM_{2.5}$ concentrations in Delhi were generally found to exceed many folds to its national ambient air quality standards (NAAQS), given by the central pollution control board (CPCB) in the year 2009 (https://cpcb.nic.in/uploads/National_Ambient_Air_Quality_Standards.pdf). Air quality of Delhi and its surrounding regions, known as National Capital Region (NCR) was recognised more than a decade ago and several preventive measures have been considered time-to-time to curb the pollution (Khanna and Sharma, 2020). These measures are shutting down of hazardous industries, banned the use of diesel vehicles (older than 10 years) within the city, use of low sulphur content of the petrol and diesel fuels, implementation of compressed natural gas (CNG) vehicles, use of cleaner fuel for domestic purposes (e.g. liquefied petroleum gas (LPG)/ piped natural gas (PNG)) and very recently traffic intervention odd-even policy (Goyal and Sidhartha, 2003; Narain and Krupnick, 2007; Saxena et al., 2012; CPCB, 2016; Chowdhury et al., 2017; Khanna and Sharma, 2020). Despite all the above efforts, the concentration of $PM_{2.5}$ and other pollutants remain at their alarming levels in Delhi and its surrounding regions, which led to major health concerns in the recent times (Maji et al., 2015; Chowdhury and Dey, 2016). Recently, a National Clean Air Programme (NCAP) was launched aiming to reduce the air pollutants, mainly $PM_{2.5}$ concentrations up to ~20–30% by 2024 in the non-attainment cities identified as the most polluted cities in India and currently the pollution levels in these cities are significantly higher than the prescribed national standards (NCAP, 2019).

The recent coronavirus pandemic (COVID-19), a highly contagious disease identified firstly in Wuhan city of China in the late December 2019, was declared a global pandemic by the World Health Organization later in March 2020 (WHO, 2020). Most countries including India have announced lockdown as precautionary measure to protect public against the spread of COVID-19. As an immediate impact of the lockdown, one change that has been observed globally is the significant improvement in air quality, which has been reported recently in many countries across the world like China, Brazil, Malaysia, Kazakhstan, Iran, Ecuador, USA etc. (Abdullah et al., 2020; Berman and Ebisu, 2020; Broomandi et al., 2020; Dantas et al., 2020; Filonchyk et al., 2020; Kerimray et al., 2020; Zalakeviciute et al., 2020). In addition, the European Environment Agency has also found a significant drop in air pollution level across the European cities, like Bergamo (Italy) and Barcelona (Spain), which showed a decline of ~ 47% and 55% in NO_2 during 16–22 March 2020 compared to the same period in 2019 (European Environmental Agency, 2020). The Government of India declared a first nation-wide stringent lockdown of 21 days from 24 March to 14 April 2020 after a 14 h of voluntary public curfew on 22 March (The Hindu, 2020), hereafter referto as Phase-1. During the lockdown, almost all the social and community mobility activities, like industrial and mass transportation have been banned with immediate effect, except some essential services, which drastically reduced the emissions across the country (Jain and Sharma, 2020; Sharma et al., 2020). Table 1 summarizes different lockdown phases along with the period and the implementation criterion, which shows stringent to conditional lockdown phases imposed as a preventive measure against the COVID-19 pandemic in India. Here, we examine the magnitude and variability of various near-surface air pollutants at an urban megacity Delhi during the lockdown amid COVID-19. The aim of our paper is two-fold: (i) to study the phase-to-phase changes in air pollution levels in terms of the impacts of COVID-19, and (ii) comparison of air pollution scenario during the same period of COVID and COVID-free years (i.e. 2020 and 2019) over the same experimental site.

2. Measurement site and experimental details

The measurement site, Delhi (28.35°N, 77.12°E, ~215 m amsl), the capital city of India, situated over the northwest part of the IGB in northern India is surrounded by various anthropogenic emission sources (CPCB, 2012). In addition to local pollution sources, Delhi receives long-range transported aerosol pollution from distant sources. During the summer, Delhi receives natural dust aerosols from adjacent (e.g., Thar) and/or far-distance (Middle East) Desert regions (Pandithurai et al., 2008; Srivastava et al., 2014). During the post-monsoon season, Delhi experiences worst air quality due to intense biomass burning in upwind states, Punjab and Haryana, and conducive meteorological conditions for accumulation of pollutants near the surface (Kaskaoutis et al., 2014; Shaik et al., 2019; Kanawade et al., 2020; Kulkarni et al., 2020).

Data pertaining to air pollutants was obtained from the Delhi Pollution Control Committee (DPCC) at the residential site, Ashok

Table 1
Different lockdown phases along with the period and implementation criterion imposed in India as a preventive measure against the COVID-19 pandemic.

Lockdown phases	Period (2020)	Implementation Criterion
Phase-1	24 March-14 April	Nearly all the social and community mobility activities, like industrial and mass transportation were suspended with immediate effect, except some of the essential services.
Phase-2	15 April-3 May	Conditional relaxation after 20 April for the regions where the spread of COVID-19 had been contained or slowed down.
Phase-3	4 May-17 May	Conditional relaxation continued and the country has been split into three different zones as Red zone (high COVID-19 cases and a high doubling rate); Orange zone (comparatively fewer COVID-19 cases than Red zone) and Green zone (without any COVID-19 cases in the past 21 days). Normal movement is permitted in the Green zone with buses limited to 50% capacity whereas in Orange zone only private and hired vehicles were allowed but no public transportation.
Phase-4	18 May-31 May	Additional relaxations, with a larger demarcation of Green, Orange and Red zones and the implementation of roadmap. Red zones were further divided into the “containment” and “buffer” zones and the local bodies were given the authority for this demarcation.

Vihar in Delhi. A population density map of Delhi is shown recently by Kishore et al. (2019) using 2011 Census data. As per the map, the present measurement site is situated in a densely populated locality in the North-West direction of Delhi, which is well connected through roads and public transport. Thus, the main pollution sources over the site could be the emissions from various residential and vehicular activities. Near-surface various air pollutants such as particulate matters, i.e. PM_{10} and $PM_{2.5}$ and gaseous pollutants, i.e. SO_2, NO_2, carbon monoxide (CO) and ozone (O_3) were obtained over the station from 01 March to 31 May during 2019 and 2020. Particulate matter measurements were based on gravimetric method using a respirable dust sampler; APM-460 BL (Envirotech) for PM_{10} and APM-550 (Envirotech) for $PM_{2.5}$. The PM_{10} sampling was done with a glass fiber filter paper of sizes 8 × 10 in. at a flow rate of 1.2 $m^3\ min^{-1}$ whereas $PM_{2.5}$ was done on a 47 mm poly tetra fluoro ethylene (PTFE, Whatman) filter paper, with a typical flow rate of 1 $m^3\ h^{-1}$. Further, SO_2, NO_2 and NO concentrations were measured using the modified West-Geake UV-Fluorescence and modified Jacob and Hochheiser methods, respectively. O_3 was measured using chemiluminescence method. More details of the measurements of these air pollutants along with their detection range and uncertainties are discussed by Kishore et al. (2019).

Moderate Resolution Imaging Spectroradiometer (MODIS) on-board NASA's AQUA satellite measures reflectance from earth surface in 36 discreet spectral bands, ranging from 0.41 to 14.4 μm and it crosses the equator at 13:30 local time. The level-3 Dark Target and Deep Blue combined Aerosol Optical Depth (AOD) data at a grid resolution of 1° × 1° (Hsu et al., 2013; Levy et al., 2013; Remer et al., 2005; Sayer et al., 2014) from collection 6.1 is used in this study. The data is downloaded from https://ladsweb.modaps.eosdis.nasa.gov/. Ozone Monitoring Instrument (OMI) onboard AURA satellite provides high resolution data sets with daily global

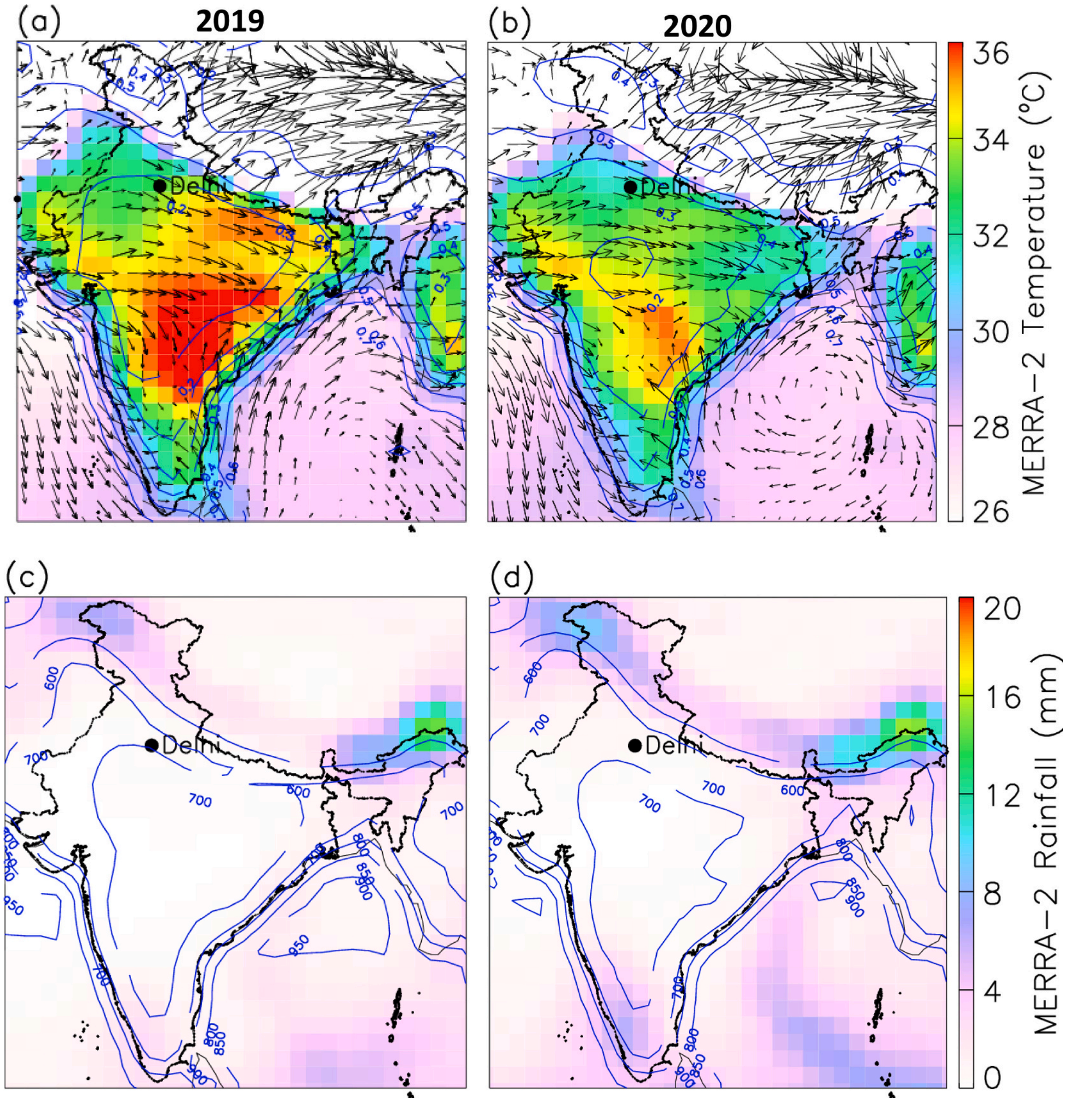

Fig. 1. (a) Averaged near-surface air temperature (color), relative humidity in fraction (contour) and wind vectors (arrows) during the pre-monsoon (March through May) of 2019. (b) same as (a) but for 2020. (c) Averaged rainfall (color) and planetary boundary layer height (contour, in hPa) during the pre-monsoon (March through May) of 2019. (d) same as (c) but for 2020.

coverage (Levelt et al., 2006). The instrument measures reflectance in wavelength range 264-504 nm. The Absorption Aerosol Optical Depth (AAOD) used in this study is retrieved using OMAERUV algorithm, which is explained in Torres et al. (2018). The level-3 AAOD at $1^{\circ} \times 1^{\circ}$ grid resolution is available from the NASA Goddard Earth Sciences, Data and Information Services Center (GES DISC; http://disc.sci.gsfc.nasa.gov).

Further, Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) derived aerosol product was examined over Delhi and its surroundings. CALIPSO is a first kind of satellite having vertically down looking lidar known as CALIOP (Cloud Aerosol Lidar with Orthogonal Polarization), which provides vertical structure of the atmosphere globally at two different channels (Winker et al., 2013). It measures elastic laser backscatter at 1064 nm and the parallel and cross polarized components of the 532 nm return signal, from which the depolarization ratio can be derived (Hu et al., 2007). Apart from various aerosol products such as total backscatter coefficient, extinction coefficient, depolarization ratio etc, CALIOP measurements have been widely used to study the specific aerosol types, which includes clean marine, dust, polluted continental, clean continental, polluted dust and smoke (Mielonen et al., 2009).

To demonstrate the potential sources aerosols and to mark the pathways of air mass at different characteristic height levels, backward trajectories obtained from the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model were also studied over the station. The air mass backward trajectories were computed for 7-day at 12:30 IST using GDAS (Global Data Assimilation System) 1^0 datasets from the HYSPLIT model (Stein et al., 2015) at three different altitude levels, i.e. 500, 1000 and 1500 m above ground level for every hour to show the evolution of these trajectories with time.

3. Results and discussion

3.1. Synoptic meteorological conditions over India

Fig. 1 shows synoptic meteorological conditions (i.e. averaged near-surface air temperature, relative humidity (RH), wind vectors, planetary boundary layer height (PBLH) and rainfall) over India during 24 March – 31 May for 2019 and 2020. The meteorological conditions were significantly different between the two years. The near-surface air temperature was found to be lower by about few degrees over continent during 2020 as compared to the year 2019. The role of absorbing aerosols in altering the atmospheric temperature, stability and large scale circulation over the Indian region has been discussed extensively in the literature, especially over the IGB (Menon et al., 2002; Moorthy et al., 2013; Nair et al., 2017; Srivastava et al., 2020). The reduction in anthropogenic absorbing aerosols associated with the enforced lockdown due to COVID-19 pandemic can cause reduction in the atmospheric warming due to such aerosols. The moisture content in the air, represented by RH in fraction was slightly higher during the year 2020 as compared to 2019. The wind circulation pattern was relatively similar between 2019 and 2020, except for a tropical cyclone (Amphan) that occurred over the Bay of Bengal in May 2020. Understanding the potential role of various surface meteorological parameters, discussed above on redistribution of air pollutants is crucial as atmosphere is the medium in which meteorological-influenced air pollutants are transported away from the source regions (Tiwari et al., 2014). In general, high temperature (indicative of deeper boundary layer) and wind speed along with the low RH favours more dispersion of air pollutants into the atmosphere compared to the relatively calm atmospheric conditions (Sharma et al., 2020). In a recent study during the lockdown, Jain and Sharma et al. (2020) have observed relatively lower surface temperature (ranging from 22 to 27 °C) and wind speed (less than 0.5 m s^{-1}) along with the higher RH (ranging from 58 to 78%) at Delhi during 1–2 weeks before the lockdown, which was not found to be the favourable atmospheric conditions for air pollutants to disperse and hence the levels of all the pollutants were high. The average PBLH during the lockdown was found to be lower than that of the previous year, which highlights the unfavourable condition for the dispersal of the pollutants. On the other hand,

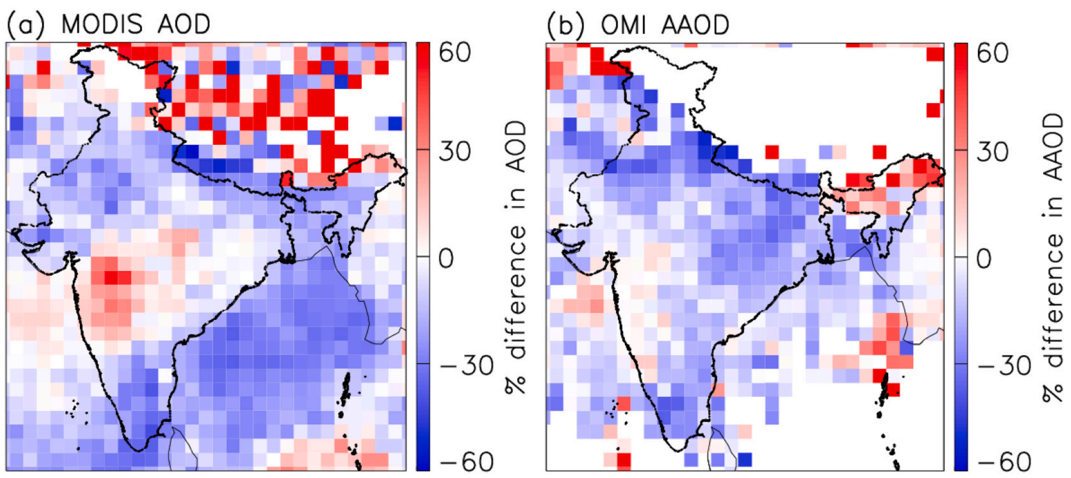

Fig. 2. The percentage difference in (a) MODIS AOD and (b) OMI Absorption AOD at 550 nm during the lockdown period (24 March – 31 May 2020) with respect to the previous year.

immediately after the lockdown, a slight increase in air temperature (ranging from 27 to 32 °C) and wind speed (ranging from 0.7–1.2 m s^{-1}) along with the lower RH in the range of 50–64% was observed over the station, which were found to be relatively favourable atmospheric conditions for increasing the dispersion of air pollutants compared to before lockdown period. The mean rainfall over the Indian region is slightly higher during the lockdown period as compared to 2019 due to the influence of Amphan cyclone over the Bay of Bengal, which again helps in the removal of pollutants. Thus, along with the lockdown, the surface meteorological parameters also

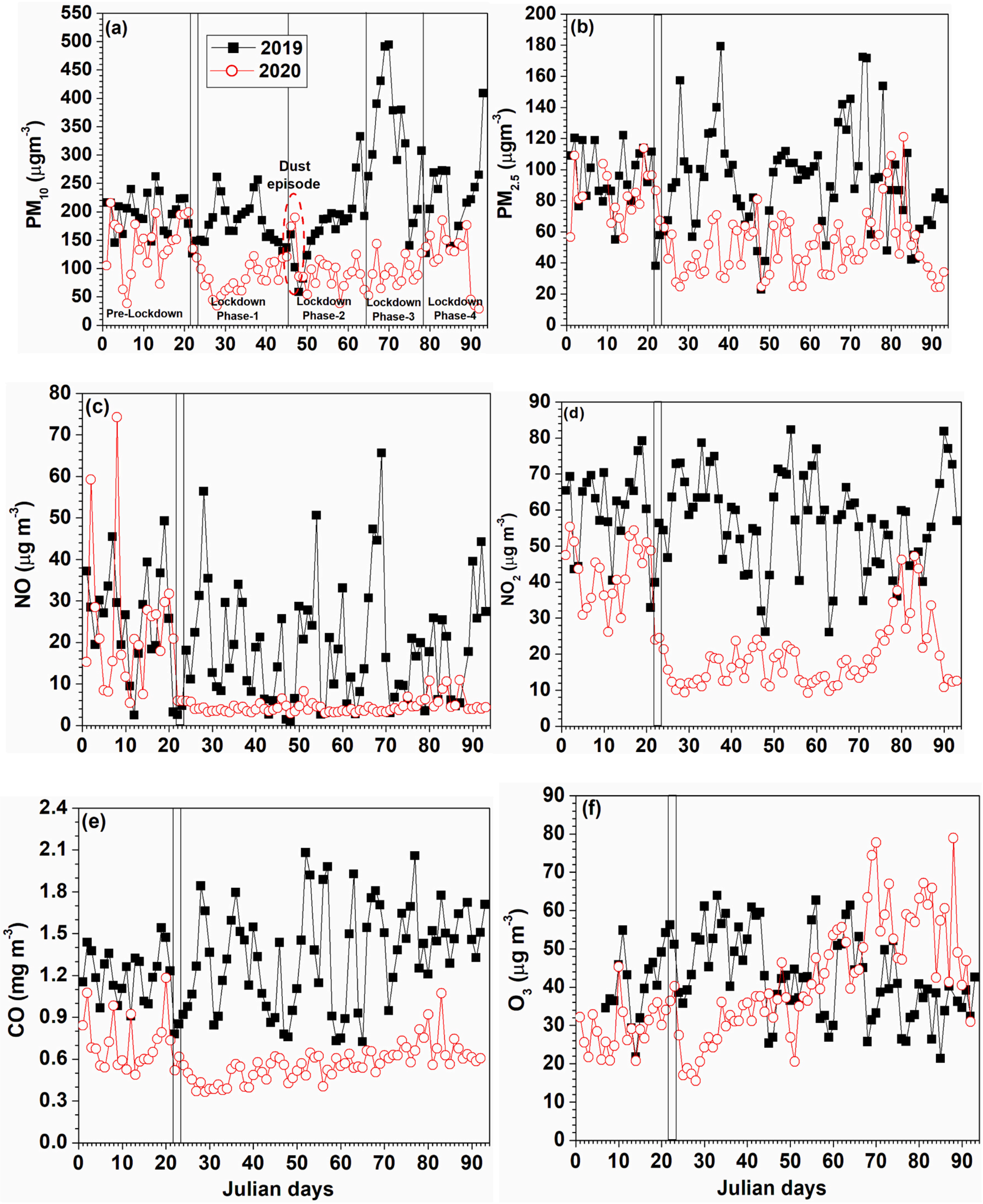

Fig. 3. Time-series of (a) PM_{10}, (b) $PM_{2.5}$, (c) NO, (d) NO_2, (e) CO and (f) O_3 in Delhi from 1 March to 31 May. Black filled squares indicate year 2019 whereas red open circle indicates year 2020. Day 1 to 92 indicates the period from 1 March to 31 May. The vertical bars separate pre-lockdown (1–21 March) from the different lockdown phases during the entire lockdown period from 24 March –31 May. 22 March was Janata curfew (one day lockdown). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

play crucial role in altering the air pollution levels of any region.

3.2. Regional aerosol characteristics from satellite measurements

We first examined the percentage change in aerosol loading over India during the entire lockdown time period (i.e. 24 March - 31 May 2020) with respect to the previous year when there was no lockdown enforced. Fig. 2(a–b) shows % difference in the MODIS retrieved AOD and OMI retrieved AAOD, respectively at 550 nm. The aerosol loading was found to reduce significantly in all over India, with elevated percentage change of ~30% across the IGB (Fig. 2a). In a recent study, Ranjan et al. (2020) also reported a significant reduction in AOD level (up to ~ 45%) across the Indian Territory during the lockdown period as compared to the long-term (2000–2019) mean AOD, with a noteworthy negative AOD anomaly of ~ 37% over the NCR region and a positive anomaly (upto 70%) over the coal mine locations. Further, the analogues reduction in the AAOD (Fig. 2b) indicates eased anthropogenic activities across the country when lockdown was enforced. In addition to the land, a significant reduction in AOD and AAOD was also observed over the oceanic region, mainly over the Bay of Bengal (BoB). Result could be associated with the reduction in the emission sources across the IGB due to the current pandemic situation. It is to be noted here that the enhanced aerosol loading over the IGB is usually the main cause of increase loading over the BoB through IGB-outflow (Srinivas et al., 2011; Tiwari et al., 2016; Singh et al., 2020). Furthermore, the IGB is situated in the vicinity of the Desert regions, and thus largely impacted by the frequent occurrence of dust aerosols during March-June (Pandithurai et al., 2008; Srivastava et al., 2014; Dumka et al., 2019) even though negative change in aerosol loading indicate that anthropogenic aerosol emission override the natural local or transported aerosols. The Sentinel - 5 P satellite observations also illustrated the improved air quality of Indian subcontinent during COVID-19 lockdown time period (Shehzad et al., 2020). Several other studies illustrated changes in near-surface air pollutants across the country, particularly in large urban areas (Singh and Chauhan, 2020; Sharma et al., 2020; Kumar, 2020; Gautam, 2020). All these studies show reduction in various air pollutants, particulate matter and gaseous, from about 40–60% over urban areas. Although, the different lockdown phases were enforced with stringent to conditional relaxation, this resulted in striking changes in pollution loading during the lockdown period. To understand this, the phase-wise changes in AOD over the Indian region, including the highly polluted IGB was studied during the lockdown period of 2020 as compared to the same periods of the previous year, i.e 2019 and shown in Fig. S1 (a–d) of the supplementary material. Though the overall decrease in the aerosol loading due to the lockdown restrictions was observed during the entire lockdown in 2020 (as seen in Fig. 2), a phase-wise increase was observed, especially across the IGB. The Phase-1 shows a drastic decrease over the IGB and coastal Bay of Bengal. The increment over the central Indian region can be attributed to the dust storms from the western desert regions, which is a characteristic of the pre-monsoon season (Sikka, 1997). Throughout the four phases of the lockdown the regions surrounding Delhi had a lesser loading as compared to the previous year. We discuss in detail as a case study for Delhi site using various near-surface air pollutants during the lockdown period in 2020 and compare air pollution loading to that with previous year.

3.3. Near-surface air pollutant characteristics from ground-based measurements

Fig. 3 (a–f) show time series of daily mean particulate matter and gaseous pollutants at Delhi during the study period from 01 March to 31 May for the year 2019 and 2020 where the period from 01 to 21 March is considered as the pre-lockdown and 24 March to 31 May is the lockdown time period. Significant day-to-day variability can be seen in both PM_{10} and $PM_{2.5}$ mass concentrations during the entire measurement period in both the years. Though, nearly similar PM_{10} and $PM_{2.5}$ concentrations were observed during the pre-lockdown period of 2019 and 2020, they started a decline immediately after imposing the lockdown from 24 March in the year 2020 and has 4–5 folds lower values as compared to 2019. Daily mean mass concentration of PM_{10} varied from 58.3 to 494.5 μgm^{-3}, with a mean value of 213 ± 81 μgm^{-3} in 2019 over the entire time period. A significant reduction in PM_{10} of ~50% was observed during 2020, when the concentration was found to vary from 28.8 to 215.9 μgm^{-3}, with a mean of 108 ± 44 μgm^{-3} in 2020. Further,

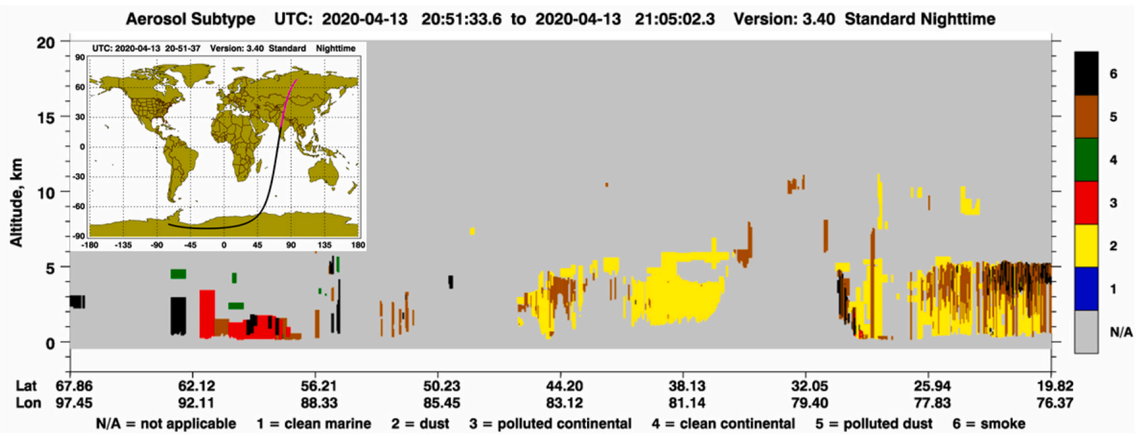

Fig. 4. CALIPSO derived aerosol subtype on 13 April 2020 over Delhi and its surroundings.

$PM_{2.5}$ over the station varied between 22.7 and 179.3 μg m^{-3}, with a mean of 93 ± 30 μg m^{-3} in 2019 whereas it varied between 24.3 and 121 μg m^{-3}, with a mean of 57 ± 24 μg m^{-3} in 2020. Both PM_{10} and $PM_{2.5}$ was found to be substantially higher than the respective 24-h NAAQS levels (PM_{10}: 100 μg m^{-3} and $PM_{2.5}$: 60 μg m^{-3}) for about 98% and 87% of the days of total observation days in 2019 whereas they were found to exceed by about 52% and 44% of the days, respectively in 2020. On the other hand, as per the world health organization (WHO) 24-h standards (PM_{10}: 50 μg m^{-3} and $PM_{2.5}$: 25 μg m^{-3}), none of the days were observed under the set limits of PM_{10} and $PM_{2.5}$ in 2019 whereas in 2020, it was found to exceed by about 92% and 94% of the days of total observation days, respectively. A momentarily enhancement in both PM_{10} and $PM_{2.5}$ concentrations was observed during 13–16 April 2020, which could be associated with the dust storm activity. To confirm this, $PM_{2.5}/PM_{10}$ ratio was analyzed during the period and observed a mean value of about 0.4, which suggests relative dominance of coarse mode dust aerosol particles over the station.

Though, almost all the anthropogenic activities (vehicular exhaust, small-scale industries etc.) were stopped during the lockdown period, we do not have any control on the natural activities, like dust storms, which was observed over the station during 13–16 April 2020. To substantiate this, CALIPSO derived aerosol product was examined over Delhi and its surroundings. Fig. 4 shows CALIPSO retrieved aerosol subtypes, which clearly indicates the enhanced dust and polluted dust aerosols over the station on 13 April 2020. These dust aerosols were found to be extended up to the height of about 5 km. Further, to demonstrate the sources of dust storm and to mark its probable pathways at three different altitude levels, i.e. 500, 1000 and 1500 m above ground level, backward air mass trajectories, obtained from the HYSPLIT model were analyzed over the station on dust days, i.e. 13 April 2020 (Fig. 5a). Also, to delineate the influence of natural sources (dust storm) on PM levels during the lockdown period, backward trajectories were also analyzed for a nearby pristine day, i.e. on 28 March 2020 (Fig. 5b) when the values of $PM_{2.5}$ and PM_{10} were lowest about 24 and 34 μg m^{-3}, respectively. During the dusty day, air masses are coming from the Middle East and Gulf regions (the main sources for natural dust aerosols) at all the heights, with longer transport path at all the higher height. On the other hand during the pristine day, air masses are mostly localized and also from the Arabian Sea and have relatively lower path at all the altitude levels. Results are well associated with the observed increase in PM levels during the dusty day and the lowest PM levels during the pristine day during the lockdown, which confirms the significant impact of natural dust activity even though the various anthropogenic activities are completely ceased due to the lockdown.

Further, a drastic reduction in the mass concentrations of NO, NO_2 and CO was also observed over the station during the lockdown period of 2020 as compared to 2019 (Fig. 3), which is relatively more pronounced for NO. As lockdown phases progressed, the noticeable increase in all the air pollutants were observed during the end of the measurement period, which is largely associated with providing some relaxation in different lockdown phases and this will be discussed in detail in the next section. Among all the gaseous pollutants, the near-surface O_3 concentrations, which are harmful for the human health, are also found to have an immediate decline

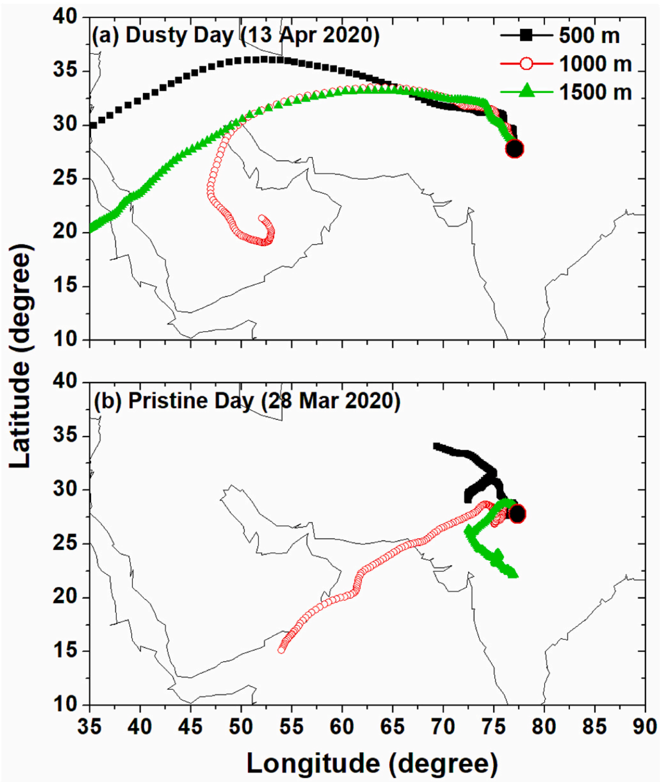

Fig. 5. 7-day air mass backward trajectories at Delhi during (a) dusty day and (b) pristine day at three different altitude levels.

just after the lockdown. Thereafter, it starts increasing gradually during the lockdown period, which could probably due to (i) observed decrease in the level of nitrogen oxides (Dantas et al., 2020) and (ii) availability of abundant solar radiation reaching to the ground during the lockdown periods which helps in photochemical reactions to produce more ozone (Devara et al., 2020). A slight decrease in O_3 was observed at the end of the measurement period, which is in-line with the observed slight enhancement in NO and NO_2. Result shows an opposite behaviour of O_3 as compared to the variability in NO and NO_2. The near-surface NO, NO_2 and O_3 are particularly critical hazardous gaseous pollutants, which are capable of causing adverse effects on human health (CPCB, 2012; Tiwari et al., 2015).

Further, to understand the impact of lockdown on the above mentioned air pollutants, an average of each pollutant has been done during the entire lockdown period from 24 March to 31 May 2020 and compared with the respective mean value for the same period during 2019 (Fig. 6). It is to be noted here that the air pollution data during the dust period, i.e. from 13 to 16 April 2020 as discussed above were excluded from this and the further analysis to avoid any misconception. The mass concentration of each pollutant, except O_3, was found to be significantly reduced over the station during the lockdown period of 2020 as compared to the normal year 2019, which is more pronounced for NO (~76%), followed by NO_2 (~68%), CO (~58%), PM_{10} (~58%) and $PM_{2.5}$ (~47%). Though, there was a significant difference in the day-to-day values of O_3, the overall mean was found to be nearly same during 2019 and 2020. As the restrictive measures reduced the emissions of $PM_{2.5}$ and PM_{10} by various transport activities and by fuel combustion in institutional and commercial buildings, but these reductions may counter-balanced by the enhanced PM emissions from the various in-house residential activities (Sicard et al., 2020).

Further, to understand the affinity between the footprint of human activities and air pollution, it is important to investigate the diurnal variability of air pollutants, particularly those of short-lived. To understand this, we analyzed the measured pollutants at Delhi on hourly basis during the lockdown period from 24 March to 31 May 2020 and compared it with the same period of 2019 (Fig. 7a–f). Significant diurnality with a morning and late-night peak was observed in each pollutant, except O_3 during both the years, which is more pronounced in 2019 compared to 2020. However, lowest values were observed in the afternoon hours. Results are largely associated with the combined effects of variations in the emission sources, surface meteorology and boundary layer dynamics. In contrary to 2019, all the pollutants, except NO_2 and O_3 were found to be relatively lower in 2020, which was associated with the reduced emissions in various sectors due to lockdown as discussed above. NO_2 was found to be relatively higher during the time between 07:00 and 20:00 h local time (LT) in 2020 as compared to 2019 whereas an opposite feature was observed during the early morning and late night hours. On the other hand, O_3 was found to be relatively higher during the time between 08:00 and 17:00 h LT in 2019 as compared to 2020 whereas an opposite feature was observed during the early morning and evening to late night hours. The observed pronounced morning peak between 07:00 and 08:00 h LT could be associated with the fumigation effect, which brings pollutants from the nocturnal residual layer shortly after the sunrise (Stull, 1999) in addition to the morning build-up of local anthropogenic activities associated with the morning traffic activities. As the day advances, increased solar intensity leads to an enhanced turbulent effect and a deeper boundary layer, leading to large dispersion of air pollutants and hence the dilution of concentration occurs near to the surface from the noon to afternoon time. The observed secondary peak in the measured air pollutants at the late night between 20:00 and 23:00 h LT could partly be attributed to the evening traffic rush mainly heavy diesel vehicles along with the shallow nocturnal boundary layer conditions and lower wind speed during night (Stull, 1999).

3.4. Impact of different lockdown phases on air pollutants

As the lockdown was imposed in a phased manner by giving little relaxation in some of the localities in cities where no COVID-19 cases were identified, a phase-wise air pollution data was analyzed for the year 2020 to understand the impacts of lockdown during

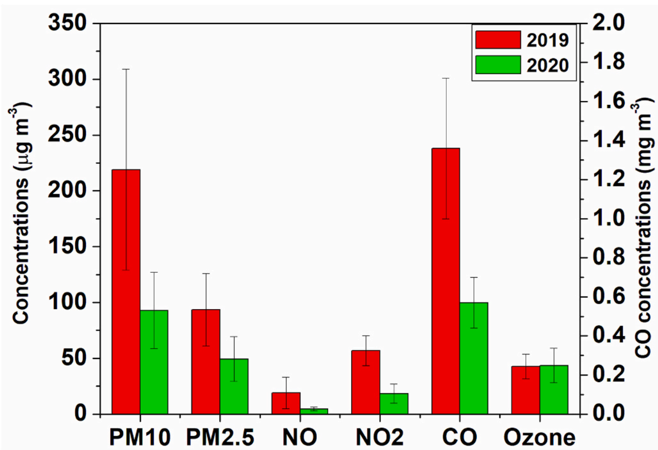

Fig. 6. Mean mass concentrations of air pollutants during the entire lockdown period from 24 March to 31 May during 2020 (green bar) and compared with the respective mean for the same period during 2019 (red bar). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

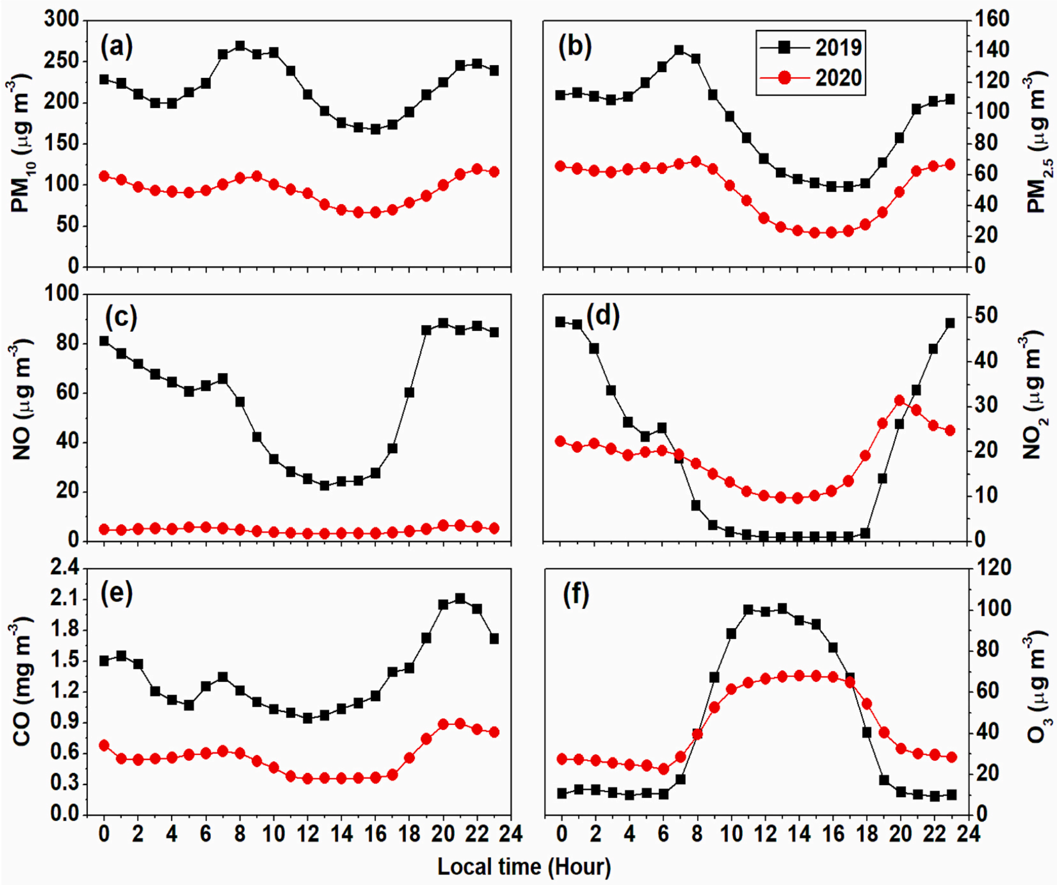

Fig. 7. A comparative diurnal variation of (a) PM_{10}, (b) $PM_{2.5}$, (c) NO, (d) NO_2, (e) CO and (f) O_3 during the lockdown period of 2019 and 2020.

different phases on air quality over the station. The diurnal variability of different air pollutants during different phases of lockdown from 24 March to 31 May 2020, including pre-lockdown period from 01 to 21 March 2020 is shown in Fig. 8(a–f). Large diurnality was observed in each pollutant during all the lockdown phases including pre-lockdown. Except O_3, a significant morning and late-night peaks are observed in all the air pollutants, which are relatively more pronounced during the pre-lockdown period compared to different lockdown phases. However, lowest values are observed in the afternoon hours. The pronounced morning peak was observed between 07:00 and 08:00 h LT during the pre-lockdown period whereas the secondary peak was observed at the late night between 20:00 and 23:00 h LT. It is to be noted here that the entry of heavy commercial diesel vehicles and trucks are allowed inside Delhi city by 11:00 pm (Bano et al., 2011; Srivastava et al., 2012). Interestingly, the diurnal concetrations of each pollutant are relatively lower in Phase-1, which could be associated with the complete shutdown imposed across the country where most of the sources responsible for poor air quality were stopped. However, the diurnal concentrations are found to increase gradually with the progression of phases having some relaxations in each phase. In contrast, a systematic and consistent diurnal variability was observed in O_3 in all the lockdown phases including pre-lockdown, with a noon time peak and an early morning and night-time low, which are more pronounced in Phases-4 and less in Phase-1. The formation of surface O_3 is largely associated with the photochemical reactions of its precursor gases, like NO, NO_2 and volatile organic compounds (VOCs) in the presence of sunlight (Seinfeld and Pandis, 1998; David and Nair, 2011).In the present study, a negative correlation was observed in O_3 with NO and NO_2, which is consistent in all the lockdown phases.

An average of each pollutant has been calculated for each phase (Fig. 9a). Interestingly, a gradual phase-wise enhancement in concentration of each pollutant was observed. All the pollutants were found to have well within their respective 24-h NAAQS values (shown by red dashed line). However, pollutants, mainly PM_{10} and $PM_{2.5}$ are found to be approaching and crossing to their respective 24-h NAAQS levels with the progression of phases. Despite the observed reduction in the concentrations of both PM_{10} and $PM_{2.5}$ compared to the respective Indian standards, they are found to be significantly higher in all the lockdown phases than the respective WHO standards. It is to be noted here that the meteorology of the region can help in controlling pollution by efficient removal, e.g. wet scavenging or can cause severe air pollution by less efficient dispersion, e.g. accumulation due to stable weather conditions (Kanawade et al., 2020). Although, the more stable atmospheric conditions during March-May 2020 as compared to 2019 as shown in Fig. 1, should lead to enhanced pollutions in the atmosphere, the observed reduced pollution loading over the station clearly indicates the reduced emissions during different phases (from stringent to conditionally relax) of lockdown amid COVID-19 pandemic. Further, the

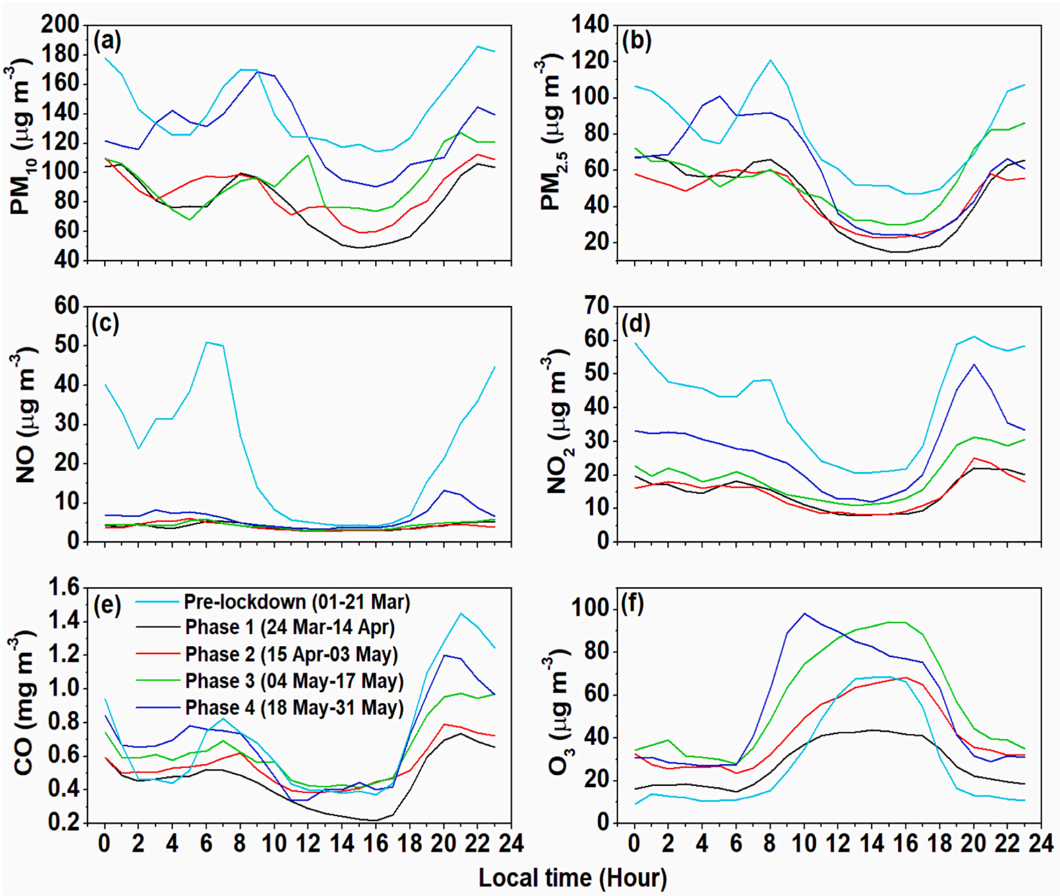

Fig. 8. A mean diurnal variation of (a) PM_{10}, (b) $PM_{2.5}$, (c) NO, (d) NO_2, (e) CO and (f) O_3 during the pre-lockdown period and in different lockdown phases.

percentage change in each pollutant during the different lockdown phases were calculated with respect to the pre-lockdown period, i.e. from 01 to 21 March 2020 and shown in Fig. 9b. As expected, all the pollutants were found to have significant reductions in Phase-1 of lockdown as compared to the other phases, which was more pronounced for NO (~83%) and NO_2 (~66%). However, a gradual phase-wise increase was observed in all the pollutants, which was more pronounced for O_3. Results could largely be associated with the gradual increase in the relaxation in various activities, like increase in the vehicular transport, few train and flight movements etc.

Both PM_{10} and $PM_{2.5}$ was found to reduce by ~ 45%, 40%, 35% and 16% and 46%, 47%, 35% and 32% during the Phase-1, Phase-2, Phase-3 and Phase-4, respectively as compared to the pre-lockdown period. However, among all the air pollutants, a steep enhancement was observed for O_3 from about −4% in Phase-1 to ~45%, 97% and 88% in Phase-2, Phase-3 and Phase-4, respectively. On the other hand, NO have relatively large reduction in all the lockdown phases as compared to the pre-lockdown period, i.e. ~83%, 83%, 82% and 73%, respectively during Phase-1, Phase-2, Phase-3 and Phase-4.

4. Conclusions

In this study, we examine the magnitude and variability in near-surface air pollutants during different phases (from stringent to conditionally relax) of lockdown amid COVID-19 pandemic during the period from 24 March to 31 May 2020. The percent change in various pollutants was compared to the previous year and also among different lockdown phases. The major findings from this study include:

- MODIS columnar AOD and OMI absorption AOD were reduced by ~30% as a result of enforced nation-wide lockdown when almost all anthropogenic activities were ceased.
- PM_{10}, $PM_{2.5}$, NO, NO_2 and CO were lower by ~58%, 47%, 76%, 68% and 58%, respectively, in Delhi during the lockdown period of 2020 as compared to 2019.
- O_3 was gradually increased with progression of lockdown phases, which is in-line with the observed decrease in NO and NO_2 and hence higher solar radiation reaching the ground.

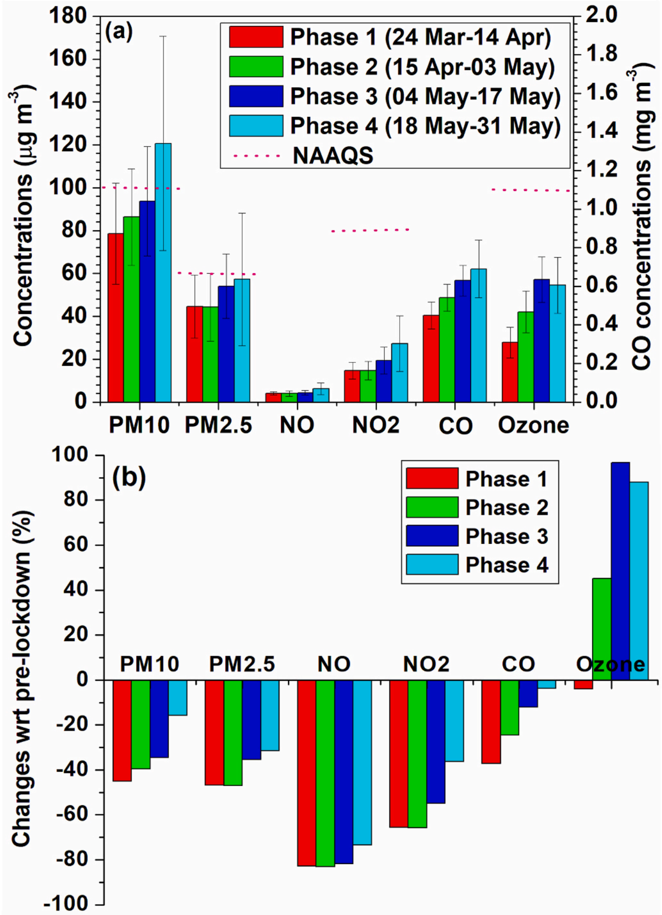

Fig. 9. (a) Mean mass concentrations of air pollutants during the difference phases of lockdown and (b) % change in air pollutants during different lockdown phases with respect to the pre-lockdown period.

- Strong diurnality along with an enhancement in the concentrations of each pollutant was observed with the progression of lockdown phases.
- A significant reduction in $PM_{2.5}$ by ~ 46%, 47%, 35% and 32%, with a steep enhancement in O_3 by about − 4%, 45%, 97% and 88%, respectively was observed during Phase-1, Phase-2, Phase-3 and Phase-4 as compared to the pre-lockdown period.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.uclim.2021.100791.

References

Abdullah, S., Mansor, A.A., Napi, N.N.L.M., Mansor, W.N.W., Ahmed, A.N., Ismail, M., Ramly, Z.T.A., 2020. Air quality status during 2020 Malaysia movement control order (MCO) due to 2019 novel coronavirus (2019-nCoV) pandemic. Sci. Total Environ. 729, 139022. https://doi.org/10.1016/j.scitotenv.2020.139022.

Bano, T., Singh, S., Gupta, N.C., Soni, K., Tanwar, R.S., Nath, S., Arya, B.C., Gera, B.S., 2011. Variation in aerosol black carbon concentration and its emission estimates at the mega-city Delhi. Int. J. Remote Sens. 32 (21), 6749–6764.

Berman, J.D., Ebisu, K., 2020. Changes in U.S. air pollution during the COVID-19 pandemic. Sci. Total Environ. 739, 139864.

Bikkina, S., Andersson, A., Kirillova, E., Holmstrand, H., Tiwari, S., Srivastava, A.K., Bisht, D.S., Gustafsson, Ö., 2019. Air quality in megacity Delhi affected by countryside biomass burning. Nat. Sustain. 2, 200–205.

Broomandi, P., Karaca, F., Nikfal, A., Jahanbakhshi, A., Tamjidi, M., Kim, J.R., 2020. Impact of COVID-19 event on the air quality in Iran. Aerosol Air Qual. Res. 20, 1793–1804. https://doi.org/10.4209/aaqr.2020.05.0205.

Chowdhury, S., Dey, S., 2016. Cause-specific premature death from ambient $PM_{2.5}$ exposure in India: estimate adjusted for baseline mortality. Environ. Int. 91, 283–290. https://doi.org/10.1016/j.envint.2016.03.004.

Chowdhury, S., Dey, S., Tripathi, S.N., Beig, G., Mishra, A.K., Sharma, S., 2017. Traffic intervention policy fails to mitigate air pollution in megacity Delhi. Environ. Sci. Pol. 74, 8–13. https://doi.org/10.1016/j.envsci.2017.04.018.

Chowdhury, S., Dey, S., Smith, K.R., 2018. Ambient $PM_{2.5}$ exposure and expected premature mortality to 2100 in India under climate change scenarios. Nat. Commun. 9 (1), 318. https://doi.org/10.1038/s41467-017-02755-y.

Cohen, A.J., Brauer, M., Burnett, R., Anderson, H.R., Frostad, J., Estep, K., Balakrishnan, K., Brunekreef, B., Dandona, L., Dandona, R., Feigin, V., Freedman, G., Hubbell, B., Jobling, A., Kan, H., Knibbs, L., Liu, Y., Martin, R., Morawska, L., Pope, C.A., Shin, H., Straif, K., Shaddick, G., Thomas, M., van Dingenen, R., van Donkelaar, A., Vos, T., Murray, C.J.L., Forouzanfar, M.H., 2017. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. Lancet 389, 1907–1918.

CPCB, 2012. National Ambient Air Quality Status and Trends–2012, August 2014. Central Pollution Control Board, Delhi, India.

CPCB, 2016. Ambient Air Quality Data at Various Locations in the Country. [WWW Document]. http://www.cpcb.gov.in/CAAQM/frmUserAvgReportCriteria.aspx. Accessed date: 10 March 2016.

Dantas, G., Siciliano, B., França, B.B., da Silva, C.M., Arbilla, G., 2020. The impact of COVID-19 partial lockdown on the air quality of the city of Rio de Janeiro, Brazil. Sci. Total Environ. 729, 139085. https://doi.org/10.1016/j.scitotenv.2020.139085.

David, L.M., Nair, P.R., 2011. Diurnal and seasonal variability of surface ozone and NO_x at a tropical coastal site: association with mesoscale and synoptic meteorological conditions. J. Geophys. Res. 116, D10303 https://doi.org/10.1029/2010JD015076.

Devara, P.C.S., Kumar, A., Sharma, P.B., et al., 2020. Multi-sensor study of the impact of air pollution on COVID-19. J. Infect. Dis. Res. 3 (S3), 22 (ISSN: 2688-6537).

Dumka, U.C., Kaskaoutis, D.G., Francis, D., Chaboureau, J.P., Rashki, A., Tiwari, S., Singh, S., Liakakou, E., Mihalopoulos, N., 2019. The role of the inter-tropical discontinuity region and the heat low in dust emission and transport over the Thar Desert, India: a pre-monsoon case study. J. Geophys. Res. 124 (23), 13197–13219. https://doi.org/10.1029/2019JD030836.

European Environmental Agency, 2020. Air Pollution goes down as Europe Takes Hard Measures to Combat Coronavirus. European Environment Agency https://www.eea.europa.eu/highlights/air-pollution-goes-down as (2020), Accessed 4th Oct 2020.

Filonchyk, M., Hurynovich, V., Yan, H., Gusev, A., Shpilevskaya, N., 2020. Impact assessment of COVID19 on variations of SO2, NO2, CO and AOD over east China. Aerosol Air Qual. Res. 20, 1530–1540. https://doi.org/10.4209/aaqr.2020.05.0226.

Gautam, S., 2020. COVID-19: air pollution remains low as people stay at home. Air Qual. Atmos. Health 13, 853–857.

Goyal, P., Sidhartha, S., 2003. Present scenario of air quality in Delhi: a case study of CNG implementation. Atmos. Environ. 37, 5423–5431.

Hsu, N.C., Jeong, M.-J., Bettenhausen, C., Sayer, A.M., Hansell, R., Seftor, C.S., Huang, J., Tsay, S.-C., 2013. Enhanced deep blue aerosol retrieval algorithm: the second generation. J. Geophys. Res. 118, 9296–9315. https://doi.org/10.1002/jgrd.50712.

Hu, Y., Vaughan, M., Liu, Z., Lin, B., Yang, P., Flittner, D., Hunt, B., Kuehn, R., Huang, J., Wu, D., Rodier, S., Powell, K., Trepte, C., Winker, D., 2007. The depolarization attenuated backscatter relation: CALIPSO lidar measurements vs. theory. Opt. Express 15, 5327–5332.

Jain, S., Sharma, T., 2020. Social and travel lockdown impact considering coronavirus disease (COVID-19) on air quality in megacities of India: present benefits, future challenges and way forward. Aerosol Air Qual. Res. 20, 1222–1236. https://doi.org/10.4209/aaqr.2020.04.0171.

Kanawade, V.P., Srivastava, A.K., Ram, K., Asmi, E., Vakkari, V., Soni, V.K., Varaprasad, V., Sarangi, C., 2020. What caused severe air pollution episode of November 2016 in New Delhi? Atmos. Environ. 222, 117125. https://doi.org/10.1016/j.atmosenv.2019.117125.

Kaskaoutis, D.G., Kumar, S., Sharma, D., Singh, R.P., Kharol, S.K., Sharma, M., Singh, A.K., Singh, S., Singh, A., Singh, D., 2014. Effects of crop residue burning on aerosol properties, plume characteristics, and long-range transport over northern India. J. Geophys. Res. 119, 5424–5444. https://doi.org/10.1002/2013JD021357.

Kerimray, A., Baimatova, N., Ibragimova, O.P., Bukenov, B., Kenessov, B., Plotitsyn, P., Karaca, F., 2020. Assessing air quality changes in large cities during COVID-19 lockdowns: the impacts of traffic-free urban conditions in Almaty, Kazakhstan. Sci. Total Environ. 730, 139179. https://doi.org/10.1016/j.scitotenv.2020.139179.

Khanna, I., Sharma, S., 2020. Could the National Capital Region Serveas a Control Region for Effective Air Qualitymanagement in Delhi?Policy Brief, CCAPC/2020/02. Collaborative Clean Air Policy Centre, New Delhi.

Kishore, N., Srivastava, A.K., Nandan, H., Pandey, C.P., Agrawal, S., Singh, N., Soni, V.K., Bisht, D.S., Tiwari, S., Srivastava, M.K., 2019. Long-term (2005-2012) measurements of near-surface air pollutants at an urban location in indo-Gangetic Basin. J. Earth Syst. Sci. 128 (3), 55.

Kulkarni, S.H., Ghude, S.D., Jena, C., Karumuri, R.K., Sinha, B., Sinha, V., Kumar, R., Soni, V.K., Khare, M., 2020. How much does large-scale crop residue burning affect the air quality in Delhi? Environ. Sci. Technol. 54 (8), 4790–4799.

Kumar, S., 2020. Effect of meteorological parameters on spread of COVID-19 in India and air quality during lockdown. Sci. Total Environ. 745, 141021.

Levelt, P.F., Oord, G.H.J., Dobber, M.R., Malkki, A., Huib, V., Johan De, V., Stammes, P., Lundell, J.O.V., Saari, H., 2006. The ozone monitoring instrument. IEEE Trans. Geosci. Remote Sens. 44, 1093–1101. https://doi.org/10.1109/TGRS.2006.872333.

Levy, R.C., Mattoo, S., Munchak, L.A., Remer, L.A., Sayer, A.M., Patadia, F., Hsu, N.C., 2013. The collection 6 MODIS aerosol products over land and ocean. Atmos. Meas. Tech. 6, 2989–3034. https://doi.org/10.5194/amt-6-2989-2013.

Maji, S., Ahmed, S., Siddiqui, W.A., 2015. Air quality assessment and its relation to potential health impacts in Delhi, India. Curr. Sci. 109 (5), 902–909.

Menon, S., Hansen, J., Nazarenko, L., Luo, Y., 2002. Climate effects of black carbon aerosols in China and India. Science 297, 2250–2253.

Mielonen, T., Arola, A., Komppula, M., Kukkonen, J., Koskinen, J., de Leeuw, G., Lehtinen, K.E.J., 2009. Comparison of CALIOP level 2 aerosol subtypes to aerosol types derived from AERONET inversion data. Geophys. Res. Lett. 36, L18804 https://doi.org/10.1029/2009GL039609.

Moorthy, K.K., Babu, S.S., Manoj, M.R., Satheesh, S.K., 2013. Buildup of aerosols over the Indian region. Geophys. Res. Lett. 40, 1011–1014. https://doi.org/10.1002/grl.50165.

Nair, V.S., Babu, S.S., Manoj, M.R., Moorthy, K.K., Chin, M., 2017. Direct radiative effects of aerosols over South Asia from observations and modeling. Clim. Dyn. 49, 1411–1428.

Narain, U., Krupnick, A., 2007. The Impact of Delhi's CNG Program on Air Quality. RFF Discussion Paper No. 07-06, Available at SSRN. https://doi.org/10.2139/ssrn.969727.

NCAP (National Clean Air Programme), 2019. Ministry of Environment. Forest & Climate Change, Government of India.

Ojha, N., Sharma, A., Kumar, M., Girach, I., Ansari, T.U., Sharma, S.K., Singh, N., Pozzer, A., Gunthe, S.S., 2020. On the widespread enhancement in fine particulate matter across the indo-Gangetic plain towards winter. Sci. Rep. 10, 5862. https://doi.org/10.1038/s41598-020-62710-8.

Pandithurai, G., Dipu, S., Dani, K.K., Tiwari, S., Bisht, D.S., Devara, P.C.S., Pinker, R.T., 2008. Aerosol radiative forcing during dust events over New Delhi, India. J. Geophys. Res. 113, D13209 https://doi.org/10.1029/2008JD009804.

Ranjan, A.K., Patra, A.K., Gorai, A.K., 2020. Effect of lockdown due to SARS COVID-19 on aerosol optical depth (AOD) over urban and mining regions in India. Sci. Total Environ. 745, 141024.
Remer, L.A., Kaufman, Y.J., Tanré, D., Mattoo, S., Chu, D.A., Martins, J.V., Li, R.-R., Ichoku, C., Levy, R.C., Kleidman, R.G., Eck, T.F., Vermote, E., Holben, B.N., 2005. The MODIS aerosol algorithm, products, and validation. J. Atmos. Sci. 62, 947–973.
Sahu, S.K., Beig, G., Parkhi, N., 2015. High resolution emissioninventory of NOx and CO for mega city Delhi, India. Aerosol Air Qual. Res. 15, 1137–1144.
Saxena, P., Bhardwaj, R., Ghosh, C., 2012. Status of air pollutantsafter implementation of CNG in Delhi. Curr. World Environ. 7 (1), 109–115.
Sayer, A.M., Munchak, L.A., Hsu, N.C., Levy, R.C., Bettenhausen, C., Jeong, M.-J., 2014. MODIS collection 6 aerosol products: comparison between Aqua's e-deep blue, dark target, and "merged" data sets, and usage recommendations. J. Geophys. Res. 119, 13965–13989.
Seinfeld, J.H., Pandis, S.N., 1998. Atmospheric Chemistry and Physics. From Air Pollution to Climate Changes. Wiley, New York, USA.
Shaik, D.S., Kant, Y., Mitra, D., Singh, A., Chandola, H.C., Sateesh, M., Babu, S.S., Chauhan, P., 2019. Impact of biomass burning on regional aerosol optical properties: a case study over northern India. J. Environ. Manag. 244, 328–343.
Sharma, S., Zhang, M., Gao, J., Zhang, H., Kota, S.H., 2020. Effect of restricted emissions duringCOVID-19 on air quality in India. Sci. Total Environ. 728, 138878. https://doi.org/10.1016/j.scitotenv.2020.138878.
Shehzad, K., Sarfraz, M., Shah, S.G.M., 2020. The impact of COVID-19 as a necessary evil on air pollution in India during the lockdown. Environ. Pollut. 266, 115080. https://doi.org/10.1016/j.envpol.2020.115080.
Sicard, P., De Marco, A., Agathokleous, E., Feng, Z., Xu, X., Paoletti, E., Rodriguez, J.J.D., Calatayud, V., 2020. Amplified ozone pollution in cities during the COVID-19 lockdown. Sci. Total Environ. 735, 139542. https://doi.org/10.1016/j.scitotenv.2020.139542.
Sikka, D.R., 1997. Desert climate and its dynamics. Curr. Sci. 72, 35–46.
Singh, R.P., Chauhan, A., 2020. Impact of lockdown on air quality in India during COVID-19 pandemic. Air Qual. Atmos. Health 13, 921–928.
Singh, A., Srivastava, A.K., Varaprasad, V., Kumar, S., Pathak, V., Shukla, A.K., 2020. Assessment of near-surface air pollutants at an urban station over the central indo-Gangetic Basin: role of pollution transport pathways. Meteorol. Atmos. Phys. (Under review).
Srinivas, B., Kumar, A., Sarin, M.M., Sudheer, A.K., 2011. Impact of continental outflow on chemistry of atmospheric aerosols over tropical bay of Bengal. Atmos. Chem. Phys. Discuss. 11, 20667–20712.
Srivastava, A.K., Singh, S., Pant, P., Dumka, U.C., 2012. Characteristics of black carbon over Delhi and Manora peak-a comparative study. Atmos. Sci. Lett. 13, 223–230.
Srivastava, A.K., Soni, V.K., Singh, S., Kanawade, V.P., Singh, N., Tiwari, S., Attri, S.D., 2014. An early south Asian dust storm during march 2012 and its impacts on Indian Himalayan foothills: a case study. Sci. Total Environ. 493, 526–534.
Srivastava, A.K., Mehrotra, B.J., Singh, A., Singh, V., Bisht, D.S., Tiwari, S., Srivastava, M.K., 2020. Implications of different aerosol species to direct radiative forcing and atmospheric heating rate. Atmos. Environ. 241, 117820.
Stein, A.F., Draxler, R.R., Rolph, G.D., Stunder, B.J.B., Cohen, M.D., Ngan, F., 2015. NOAA's HYSPLIT atmospheric transport and dispersion modeling system. Bull. Amer. Meteor. Soc. 96, 2059–2077.
Stull, R.B., 1999. An Introduction to Boundary Layer Meteorology. Springer, New York, p. 620.
The Hindu, 2020. https://www.thehindu.com/news/national/pm-announces-21-day-lockdown-as-covid-19-toll-touches-10/article31156691.ece, 24 March 2020.
Tiwari, S., Bisht, D.S., Srivastava, A.K., Pipal, A.S., Taneja, A., Srivastava, M.K., Attri, S.D., 2014. Variability in atmospheric particulates and meteorological effects on its mass concentrations over Delhi, India. Atmos. Res. 145-146, 45–56.
Tiwari, S., Dahiya, A., Kumar, N., 2015. Investigation into relationships among NO, NO_2, NO_x, O_3 and CO at an urban background site in Delhi, India. Atmos. Res. 157, 119–126.
Tiwari, S., Mishra, A.K., Singh, A.K., 2016. Aerosol climatology over the bay of Bengal and Arabian Sea inferred from space-borne radiometers and Lidar observations. Aerosol Air Qual. Res. 16, 2855–2868.
Tobler, A.K., Bhattu, D., Canonaco, F., Lalchandani, V., Shukla, A., Thamban, N.M., Mishra, S., Srivastava, A.K., Bisht, D.S., Tiwari, S., Singh, S., Močnik, G., Baltensperger, U., Tripathi, S.N., Slowik, J.G., Prévôt, A.S., 2020. Chemical characterization of $PM_{2.5}$ and source apportionment of organic aerosol in New Delhi, India. Sci. Total Environ. 745, 140924. https://doi.org/10.1016/j.scitotenv.2020.140924.
Torres, O., Bhartia, P.K., Jethva, H., Ahn, C., 2018. Impact of the ozone monitoring instrument row anomaly on the long-term record of aerosol products. Atmos. Meas. Tech. 11, 2701–2715.
Upadhyaya, A., Dey, S., Goyal, P., Dash, S.K., 2018. Projection of near-future anthropogenic $PM_{2.5}$ over India using statistical approach. Atmos. Environ. 186, 178–188.
WHO, 2016. WHO Global Urban Ambient Air Pollution Database (Update 2016).
WHO, 2020. Coronavirus Disease 2019 (COVID-19) Situation Report −63. Available at. https://www.who.int/docs/default-source/coronaviruse/situation-reports/20200323-sitrep-63-covid-19.pdf?sfvrsn=b617302d_4.
Winker, D.M., Tackett, J.L., Getzewich, B.J., Liu, Z., Vaughan, M.A., Rogers, R.R., 2013. The global 3-D distribution of tropospheric aerosols as characterized by CALIOP.Atmos. Chem. Phys. 13, 3345–3361.
Wu, Y., 2012. Understanding Economic Growth in China and India: A Comparative Study of Selected Issues. World Scientific.
Zalakeviciute, R., Vasquez, R., Bayas, D., Buenano, A., Mejia, D., Zegarra, R., Diaz, A., Lamb, B., 2020. Drastic improvements in air quality in Ecuador during the COVID-19 outbreak. Aerosol Air Qual. Res. 20, 1783–1792.