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An analysis of particulate pollution using urban aerosol pollution island intensity over Delhi, India

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Abstract The accent of the present study is determination of Urban Aerosol Pollution Island (UAPI) intensity and spatial variability in particulate matter concentration (PM_{10} and $PM_{2.5}$) over Delhi. For analysis, the hourly concentration dataset of $PM_{2.5}$ and PM_{10} from January 2019 to December 2020 was obtained from ten air quality monitoring stations of Delhi. Additionally, UAPI Index has been calculated to assess the intensity of particulate pollution. The daily, monthly, and annual variations in the trends of PM_{10}, $PM_{2.5}$, and UAPI index along with related meteorological parameters have been analyzed. Particulate pollution peaked majorly during two seasons, i.e., summer and winter. The highest concentration of PM_{10} was observed to be 426.77 μg/m^3 while that of $PM_{2.5}$ was observed to be 301.91 μg/m^3 in January 2019 for traffic-affected regions. During winters, higher $PM_{2.5}$ concentration was observed which can be ascribed to increased local emissions and enhanced secondary particle formations. While the increase in PM_{10} concentrations led to an increment in pollution episodes during summers over most of the sites in Delhi. The UAPI index was found to be declining in 2020 over traffic affected regions (77.92 and 27.22 for 2019 and 2020, respectively) as well as in the background regions (64.91 and 19.80 for 2019 and 2020, respectively) of Delhi. Low traffic intensity and reduced pollutant emission could have been responsible for the reduction of UAPI intensity in the year 2020. The result indicates that lockdown implemented to control the COVID-19 outbreak led to an unexpected decrease in the PM_{10} pollution over Delhi.

Keywords Air Pollution · PM_{10} · $PM_{2.5}$ · Traffic Emissions · UAPI

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Nomenclature

AOD	Aerosol optical depth
COVID-19	Coronavirus Disease 2019
CPCB	Central Pollution Control Board
DAAC	Distributed Active Archive Center
LAADS	Level-1 and atmosphere archive & distribution system
LULC	Land use land cover

MAIAC	Multi-angle implementation of atmospheric correction
MODIS	Moderate resolution imaging spectroradiometer
NAAQS	National ambient air quality standards
NO_2	Nitrogen dioxide
PM	Particulate matter
RS	Rural stations
SAT_MPI	SATellite-based Multi-Pollutant Index
UAPI	Urban Aerosol Pollution Island
UBS	Urban background stations
UTS	Urban traffic stations
WHO	World Health Organization

Introduction

In the present world, the increasing global population and related negative impacts is a major problem. Over the last century, the world's population has increased dramatically from 717 million in 1750 to 6 billion in 2000, and is estimated to exceed 8 billion by 2025 (Cetin, 2016; Cetin & Jawed, 2022; Sevik, 2021). The development of industries has led majority of this population to concentrate in metropolitan regions (Kilicoglu et al., 2020; Gungor et al., 2021; Cetin & Jawed, 2022). In 2000, about 2.9 billion people (47% of the world's population) lived in cities, which is anticipated to climb to 60 to 90% of the world's population by 2030 (Cetin & Sevik, 2016a; Yuksel, 2008). Moreover two-third of Europe's total population lives in cities (Cetin et al., 2019). Several studies have found that the ongoing migration of people from rural to urban area will increase further (Cetin et al., 2017, 2019; Kaya et al., 2019). Most of the international and planetary scale problems arises due to population expansion and its migration from rural to urban regions (Cetin et al., 2019; Elsunousi et al., 2021). Environmental pollution, ecological degradation, food scarcity (Sevik et al., 2020), destruction of the ecological balance, destruction of green spaces, increased conflicts, and a higher risk of large-scale disasters such as pandemic are just a few examples of such issues (Abualqumboz et al., 2017; Begum et al., 2008; Cetin, 2015; Cetin et al., 2017, 2019; Sevik et al., 2019, 2021). One of the most serious of these issues is air pollution in metropolitan areas which in certain cities has reached levels that endangers human life and health (Abualqumboz et al., 2017; Cetin & Sevik, 2016b; Sevik et al., 2019). Approximately 92% of the global population is reported to be residing in regions experiencing poor air quality (Cetin, 2020). Lastly, air pollution is reported to kill one in every eight people globally (Cetin et al., 2022). The aforementioned facts provide sufficient evidences that air pollution over urban areas requires immediate attention for the improvement of air quality of the earth.

In urban space, continuous pollutant emissions are primarily attributed to an increase in anthropogenic activities, such as emissions from industrial units, automobiles and day-to-day household activities. This increase in anthropogenic activities results in higher particulate concentration in the urban atmosphere than in the surrounding rural atmosphere (Kerschbaumer & Lutz, 2008; Vardoulakis & Kassomenos, 2008). The term Urban Pollution Island (or Urban Aerosol Pollution Island) was introduced to describe such a higher concentration of air pollutants in urban agglomerations. "Urban Aerosol Pollution Island (UAPI)" is defined as the higher concentration of particulate matter in an urban area than in the surrounding areas (Crutzen, 2004; Li et al., 2018). Airborne particulate matter includes all solid particles (fine or coarse) and liquid droplets (Singh et al., 2020). Based on aerodynamic diameter, particles are majorly sub-categorized into PM_{10} and $PM_{2.5}$. From direct and indirect effects on the climatic system and radiative forcing to detrimental impacts on human health, higher concentration of these particles imparts a wide range of negative impacts on the biosphere (Satheesh & Ramanathan, 2000; Pope & Dockery, 2006; Stocker et al., 2013; Field et al., 2014; Wang et al., 2014).

Humankind is well accustomed to the ever-increasing concentration of air pollutants. Scientists and various governmental agencies have quantified the impact of these air pollutants by air quality indexing system (e.g., Bishoi et al., 2009; Cairncross et al., 2007; Cheng et al., 2004; Gorai et al., 2014; Mandal et al., 2012). A handful of these indices incorporate satellite datasets. One such example is a satellite-based multi-pollutant index (SAT_MPI) proposed by Cooper et al. (2012) in which the space-borne measurements of particulate matter (PM) and nitrogen dioxide (NO_2) were taken into consideration. Additionally, most of these indexing systems have failed to include the individual impact of air pollutants on human health. This brought forth a need to develop one such air quality index which is inclusive of both satellite datasets and the impact of air pollution on human health. Regular air quality assessment is important for urban environments where the level of air pollution is dangerously high (Fenger, 1999).

In recent times, studies addressing urban particulate pollution and UAPI have become a new focal point for the atmospheric research community (Baklanov et al., 2016; Sokhi et al., 2017). Even though extensive observations have been carried out to study particulate pollution in urban spaces, the urban–rural difference in particulate matter concentration and the causative factors are yet to be quantitatively understood (Crutzen, 2004; Monn et al., 1995; Salmond et al., 2018). For this, the UAPI index proves to be an efficient tool, as it represents the urban–rural difference in particulate matter concentration. UAPI and urban particulate matter might seem synonymous, but in reality, the characteristics of both are different from each other. For example, the urban sectors of a city may exhibit higher aerosol concentration, but probably due to the huge number of industries set up in rural areas the urban–rural difference might be small (Cao et al., 2016). Therefore, understanding the UAPI phenomenon along with its underlying factors and quantifying its intensity is important to properly understand the urban–rural difference of aerosol concentration.

At the beginning of the year 2020, lockdown implementation to curb the outbreak of COVID-19 began across several nations after WHO declared the situation as a matter of public health emergency of international concern and the spread of global pandemic (Tian et al., 2020). With the confirmation of the first COVID-19 positive case on 30 January 2020 followed by the rapidly spreading infections, the government of India also planned and imposed lockdown in Phase – I (25 March–14 April 2020), Phase – II (15 April–3 May 2020) and so on (Gettleman & Schultz, 2020; Pathakoti et al., 2020; UN news, 2020). Apart from essentials, all other activities such as industrial production and inter and intra-state transportation were paused for this duration. During the lockdown, billions of citizens were advised to stay at home, which led to the fall in the national economy. However, the extended cessation of vehicular and industrial activities resulted in a substantial reduction in air pollution levels across India (Pathakoti et al., 2020). Being an Indian megacity, the same was true for Delhi and the down surge in pollutant concentration has been quantified and presented in several research papers (e.g., Gautam et al., 2021; Mahato et al., 2020; Ravindra et al., 2021; Srivastava et al., 2020).

The accent of the present study is to determine UAPI intensity and spatial variability in particulate matter concentration (PM_{10} and $PM_{2.5}$) over Delhi for the years 2019 and 2020 to establish the existence of the phenomenon over Indian megacities. Delhi is one of the most polluted cities in the world with an annual mean $PM_{2.5}$ concentration of 143.0 ± 17.8 μg/m^3 (Cheng et al., 2016) and requires continuous monitoring of air pollutant concentration. With the human population reaching 16.3 million as of 2011 (ENVIS CPCB, 2016), people residing within Delhi are continuously exposed to polluted air loaded with toxic substances. This is a first study to assess UAPI phenomena over Delhi which has emerged as a new focal area in atmospheric research community. Additionally, the study provides new insights on quantifying the effect of COVID-19 lockdown on air pollution over urban, suburban and rural areas of Delhi. The results of the study will aid decision makers to develop counter-measures for the abatement of particulate pollution by providing the variability characteristics of particulate matter and its association with local meteorology. This will aid in controlling the poisonous urban atmosphere and protecting the residents from adverse health effects.

Materials and methods

Site description

Delhi (28.7041° N, 77.1025° E, 216 m altitude above mean sea level) is the national capital of India to be found around 160 km south of the Himalayas (Saksena, 2009). It has an area of 1484 km^2. Located in the subtropical belt of the Northern Temperate geographical region, the city experiences scorching summers, average precipitation, and cold winters. As per 2011 census of India, it is a massive metropolitan area having a population density of 11,312 people per square kilometer. Delhi is surrounded by the heavily industrialized National Capital Region along with Haryana and Uttar Pradesh. According to the Delhi Economic Survey 2018–2019 report, the number of cars in the national capital has increased to 10.9 million by March 2018, including nearly 7 million two-wheelers (Planning Department, Government of National Capital

Territory of Delhi, 2019). This rapid increase in automobiles further results in increased traffic congestion and finally enhanced air pollution which has become a major concern (Advani & Tiwari, 2005).

Out of 38 air monitoring stations in Delhi, 10 stations were selected for the analysis. Further, we have classified the monitoring station into three categories i.e. urban traffic stations (UTS), urban background stations (UBS), and rural stations (RS). This delineation of the monitoring stations was performed based on road network clusters. Additionally, Land Use Land Cover (LULC) mapping was utilized to reinforce the station delineation method. Land Use Land Cover map was created using Sentinel—2A Level—1C product (Copernicus Sentinal-2, 2021). Figure 1 depicts the exact locations of the selected monitoring stations along with the delineation into UTS (represented by the green circle), UBS (represented by the green square), and RS (represented by the green triangle).

We have classified those monitoring stations into Urban Traffic Station (UTS) category which are surrounded by large urban built-up and a very dense road network. This was done to assess the effect of traffic-related emissions on PM concentrations in areas in close proximity. Further, through literature survey, we have found that all stations listed as UTS usually suffers from poor air quality as compared to other locations. Secondly, stations classified as Urban Background Station (UBS) are also urban areas experiencing slightly cleaner air quality than UTS and are either situated far from primary road network or are not surrounded heavily by roads. Also, UBS are locations situated close to green area (Fig. 1) and hence may not be affected much by heavy traffic congestions. This delineation was done to quantify the effect of other emission sources on PM concentration. Lastly, we have selected one rural station (RS) situated far away from urban centers to quantify background level of particulate matter.

Detailed information on the monitoring stations and the dataset acquired has been summarised in Table 1.

Instruments for measurement

The current study utilizes hourly concentration dataset of PM_{10} and $PM_{2.5}$ at selected monitoring stations (Table 1). Hama et al. (2020) have discussed the monitoring instruments for PM_{10} and $PM_{2.5}$ data collection. $PM_{2.5}$ has been measured by the BAM 1020 which works on the principle of Beta ray attenuation and automatically measures and records airborne particulate matter concentration levels (in milligrams or micrograms per cubic meter).

Particulate matter (PM_{10} and $PM_{2.5}$) dataset

Dataset for particulate matter (PM_{10} and $PM_{2.5}$) was acquired on 1-h basis for the period of January 2019 to December 2020 from CPCB (Central Pollution Control Board) website (source: http://www.cpcb.gov.in/CAAQM/frmUserAvgReportCriteria.aspx). These datasets were used to develop diurnal average concentration data which was further averaged to obtain monthly and annual concentration data. Lastly, UAPI intensity was calculated from the collected dataset. The formula used for the UAPI intensity calculation followed Li et al. (2020).

$$UAPI\_T = Mean\ Pollutant\ Concentration\ at\ UTS - Mean\ Pollutant\ Concentration\ at\ RS \quad (1)$$

$$UAPI\_B = Mean\ Pollutant\ Concentration\ at\ UBS - Mean\ Pollutant\ Concentration\ at\ RS \quad (2)$$

where UAPI_T = Pollution Island Intensity at UTS.

UAPI_B = Pollution Island Intensity at UBS.

Lastly, the percentage decrease in PM_{10} concentration was calculated using Eq. 3:

$$Percentage\ Decrease = \left(\frac{Mean\ Pollutant\ Concentration\ for\ 2019 - Mean\ Pollutant\ Concentration\ for\ 2020}{Mean\ Pollutant\ Concentration\ for\ 2019} \right) \times 100 \quad (3)$$

Meteorological data

To study the impact of local meteorological conditions on UAPI intensity over the monitoring stations, hourly meteorological data for ambient temperature, wind speed and direction, solar radiation, and relative

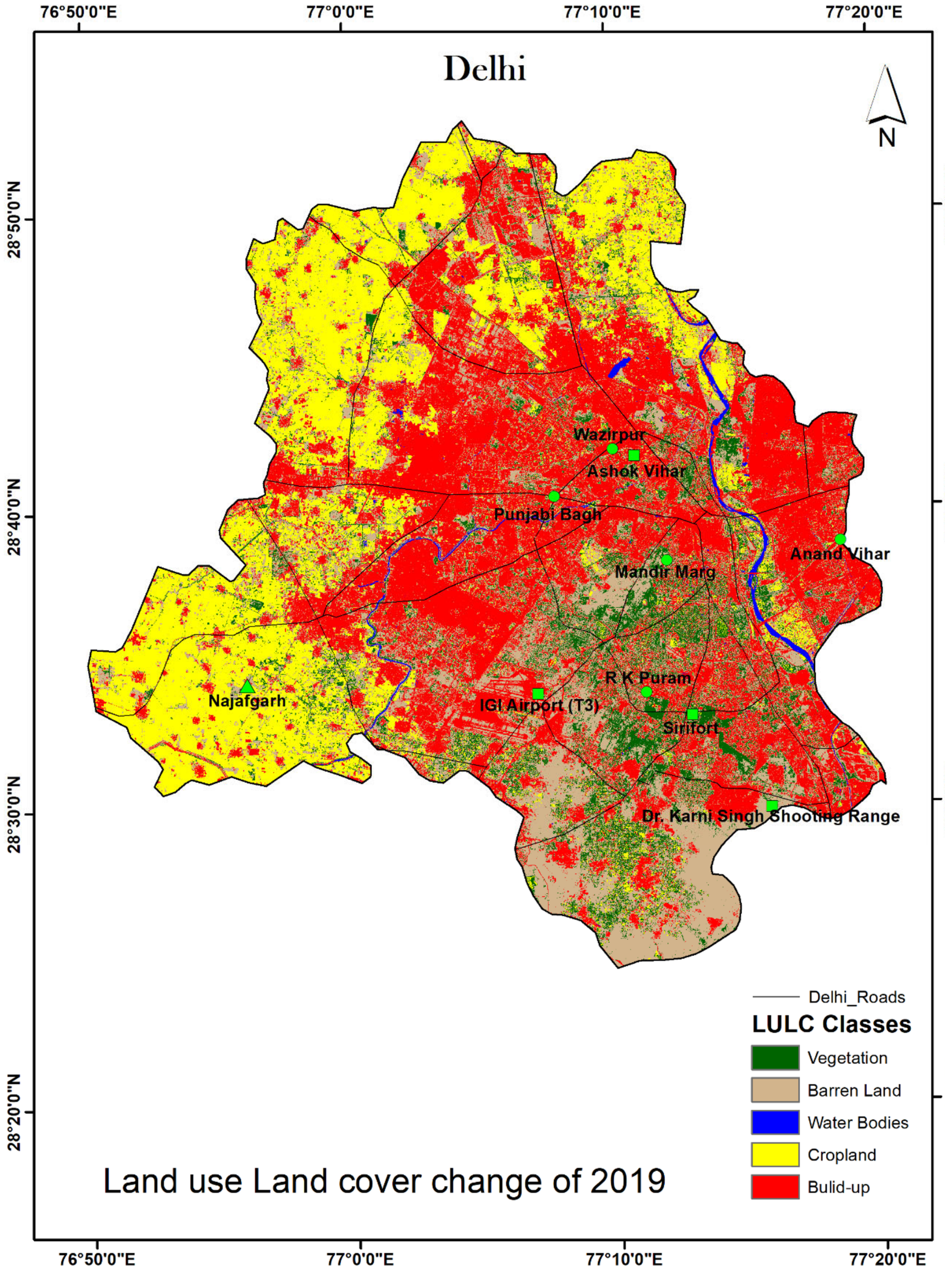


Fig. 1 Study Area Map representing delineated monitoring stations for the current analysis

Table 1 Details of selected monitoring stations and acquired datasets

Station name	*Latitude*	*Longitude*	*Station type*	*PM dataset*	*Meteorological dataset*
Anand Vihar, DPCC	28.6468	77.3160	Urban traffic	√	√
Punjabi Bagh, DPCC	28.6740	77.1310	Urban traffic	√	√
Mandir Marg, DPCC	28.6364	77.2011	Urban traffic	√	√
R K Puram, DPCC	28.5633	77.1869	Urban traffic	√	√
Wazirpur, DPCC	28.6998	77.1655	Urban traffic	√	√
Ashok Vihar, DPCC	28.6954	77.1817	Urban background	√	√
IGI Airport (T3), IMD	28.5628	77.1180	Urban background	√	-
Dr. Karni Singh Shooting Range, DPCC	28.4986	77.2648	Urban background	√	√
Sirifort, CPCB	28.5504	77.2159	Urban background	√	-
Najafgarf, DPCC	28.5702	76.9338	Rural	√	√

humidity were collected from CPCB database (source: http://www.cpcb.gov.in/CAAQM/frmUserAvgReportCriteria.aspx) for the same study duration (January 2019 to December 2020).

Satellite data description–moderate resolution imaging spectroradiometer

Moderate resolution imaging spectroradiometer (MODIS) — onboard Terra and Aqua — is an essential space-borne instrument that aids in representing the columnar aerosol optical properties by providing measurements for columnar light extinction by ambient aerosol during the satellite overpass. Both Aqua and Terra cross the equator during the daytime (01:30 PM – Aqua and 10:30 AM – Terra). One of the crucial parameters to estimate the air quality of a region is Aerosol Optical Depth or AOD (Soni et al., 2021). For evaluating the variations in AOD, MCD19A2, a combined product of MODIS level-2 collection version 6.0 gridded data over land surfaces has been extracted. MCD19A2 product is available daily at 1-km pixel resolution and retrieval algorithm applied is Multi-Angle Implementation of Atmospheric Correction (MAIAC) algorithm. The product (Lyapustin & Wang, 2018) was acquired from the Level-1 and Atmosphere Archive & Distribution System (LAADS) Distributed Active Archive Center (DAAC), located in the Goddard Space Flight Center in Greenbelt, Maryland (https://ladsweb.nascom.nasa.gov/). It is a multi-layer scientific dataset containing the AOD at 470 nm in the blue band and AOD at 550 nm in the green band. It also generates other aerosol properties like fine mode fraction over water, column water vapor over land and clouds (in cm), and smoke injection height (m above ground). AOD data was extracted at 550 nm (level 1.0 collection version 6.0). A detailed account of the retrieval techniques applied can be found from Levy et al. (2013). The current study covers mean AOD for May 2019 and 2020.

Data processing

The ground-based dataset for particulate matter and meteorological parameters was acquired at every 1 h from the CPCB website. The time period for the collection of dataset is from January 2019 to December 2020. Further, dates having no data either in particulate matter or in meteorological parameters dataset have been eliminated from the analysis. Measurements of more than 104 days (the minimum measurement data taken into consideration for annual mean calculation as per NAAQS, CPCB) have been taken into consideration for each year in the present study.

After filtering, the hourly dataset was utilized to obtain daily mean concentration data for PM and diurnal averaged meteorological parameter dataset. These daily averaged datasets were utilized to develop monthly and annual means for PM concentration and meteorological parameters. After obtaining all the required datasets for each stations, the dataset for UTS, UTB, and RS have been grouped together and again averaged to obtained PM concentration and meteorological parameters for UTS, UBS and RS, respectively. For the assessment of UAPI intensity, we have used Eqs. 1 and 2, respectively. The monthly and annual concentrations of PM_{10} have been utilized for monthly and annual UAPI intensity calculation. Percentage decrease in PM_{10} concentration was also calculated with the help of Eq. 3.

At last, MODIS retrieved AOD considering each tiles of each day falling within the boundary of study area was used for analysis. Pre-processed MODIS AOD Level-2 dataset was acquired from LAADS DAAC. A total of 119 images were obtained for May 2019 and May 2020, respectively. The obtained images were then processed utilizing steps like removing null values (−9999), multiplying the image with scale factor (0.001) and clipping. Lastly, processed images were utilized to obtain AOD plots for May 2019 and May 2020, respectively. All the steps were performed using QGIS (v3.16) software.

Results and discussion

The spatial distribution of mean AOD has been presented for May 2019 and May 2020 along with the difference (Fig. 2a–c). The urban cluster of Delhi has been highlighted (using the red circle) to evaluate the variability in pollution levels. The month of May was selected to capture the change in AOD with and without the traffic emissions, as COVID-19 lockdown was implemented at the end of March 2020. For May 2019, the AOD concentration lies approximately between 0.35 and 0.50 (Fig. 2a) which decreased to 0.30–0.40 in May 2020 (Fig. 2b) with a difference ranging from less than −0.2 to 0 (Fig. 2c). This indicates that during May 2020 mean AOD values were lower as compared to the mean AOD values for May 2019 within the urban cluster probably due to the cessation of automobile movement during COVID-19 lockdown (Soni et al., 2021).

Figure 3 presents the variation in PM_{10} and $PM_{2.5}$ concentrations for four months (i.e., January, May, August, and November) of 2019 and 2020 over UTS and UBS, respectively. A drop-in concentration of both PM_{10} and $PM_{2.5}$ was observed in the year 2020, with an exception of November. A massive down surge in PM_{10} concentration was observed during May month over UTS, i.e., 51.52% (264.56 μg/m^3 in 2019 and 128.25 μg/m^3 in 2020) as well as UBS, i.e., 52.19% (253.54 μg/m^3 in 2019 and 121.21 μg/m^3 in 2020). This decrease could be attributed to the implementation of a nationwide lockdown to curb the coronavirus outbreak.

Figure 4a to h present the diurnal variation in PM_{10} and $PM_{2.5}$ concentration for the months (i.e., January, May, August, and November) of 2019 and 2020 over UTS and UBS, respectively. For the year 2019, diurnal variation of PM_{10} and $PM_{2.5}$ showed a bimodal distribution during January, May, and November. The first peak was observed in the morning (~08:00–10:00), while the second was observed in the evening (~15:00–16:00). Particulate matter concentration decreased for the year 2020, but diurnal variation remained the same as for 2019. The highest concentration for PM_{10} was observed to be 426.77 μg/m^3 during January 2019 over UTS while that for $PM_{2.5}$ was observed to be 301.91 μg/m^3 during January 2019 over UTS.

For January, it can be seen from Fig. 4a and b that the concentrations of both PM_{10} and $PM_{2.5}$ began to increase from 06:00 to 09:00 h, with peak values observed at 09:00 (i.e., for the year 2019 and 2020). After this, the concentration started decreasing and continuous dipping values were prominent from 10:00 to 16:00 h. An upsurge in the concentration can be seen again from 17:00 to 22:00 h. To conclude, stagnant atmospheric conditions, prevention of diffusion of pollutants, decreased long-range transport of particulate matter, and enhanced secondary particle formation resulted in higher $PM_{2.5}$ concentrations for winter months (Mohan & Bhati, 2009; Tiwari et al., 2013a, b; Payra et al., 2016; Kanawade et al., 2020).

Figure 4 c and d represent the diurnal variation in particulate matter concentration for May. The morning peak value for PM_{10} was observed at 08:00, while the evening peak was observed at 22:00 for both years. The concentration underwent continuous down surge from 12:00 to 16:00 h. An almost similar diurnal variation is exhibited by $PM_{2.5}$ with peak concentration observed at 07:00 and 23:00 for both years. $PM_{2.5}$ concentration decreased during daytime with an observable dip in values from 11:00 to 16:00 h.

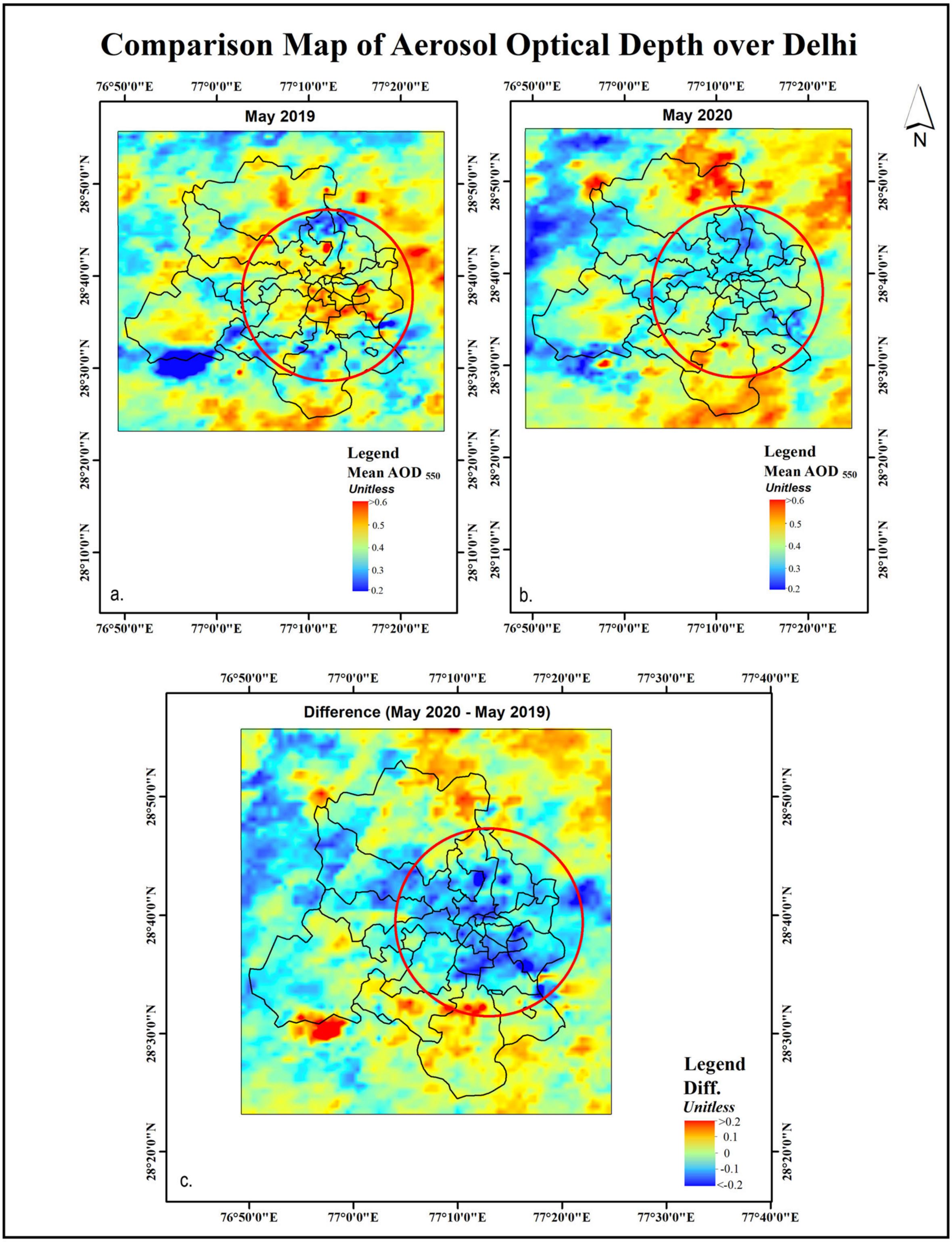


Fig. 2 Spatial plots for mean aerosol optical depth for May 2019 (**A**); May 2020 (**B**) and difference, i.e., May 2020–May 2019 (**C**) over Delhi

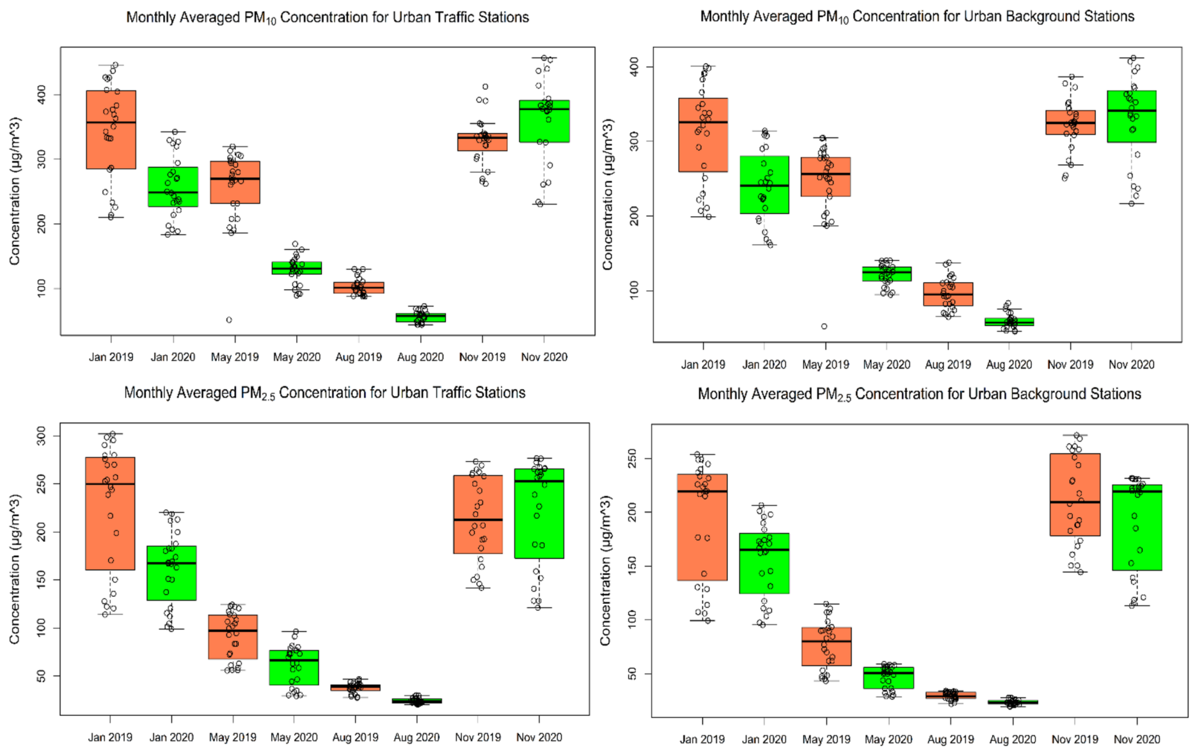
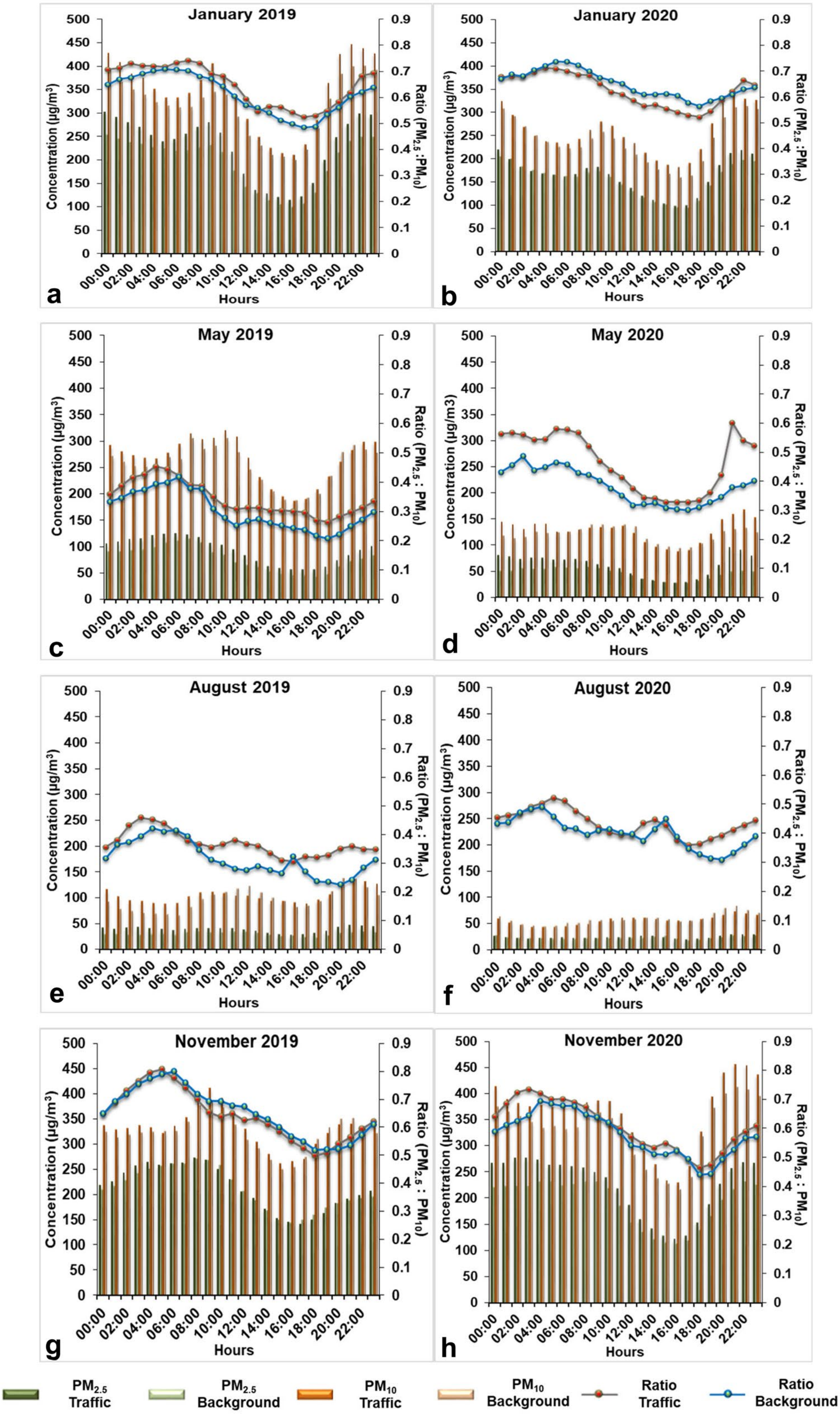


Fig. 3 Box plot of monthly averaged PM_{10} and $PM_{2.5}$ concentrations along with strip chart

The month of August experienced a decrease in particulate matter concentration with an inconsistent diurnal variation. Heavy precipitation could be a probable reason behind this decrease, as it washes off a large amount of ambient particulate matter along with other pollutants (Murari et al., 2017). Lastly, the diurnal variations in concentration PM_{10} and $PM_{2.5}$ during November were examined and almost similar fluctuations to that observed in January were observed. November falls in the post-monsoon season which is characterized by large-scale emission of particulate matter (particularly in Delhi) and prevailing meteorological conditions favor the increase in concentration. PM_{10} concentration in November 2020 was high in comparison to November 2019. This increase could be attributed to local meteorological conditions as well as enhanced emissions. The wind speed was lower in November 2020 than in November 2019 for UTS (1.15 to 0.44 m/s and 1.20 to 0.55 m/s for November 2020 and 2019, respectively) and UBS (0.82 to 0.37 m/s and 0.89 to 0.51 m/s for November 2020 and 2019, respectively) as evident from Table 2. It has been reported that calm wind inhibits the dispersion of the pollutant and increases the concentration of PM over a restricted area (Galindo et al., 2011). In addition, the light festival of India (Diwali) was celebrated amid November month (14 to 15 November, 2020) in the year 2020 while it was celebrated in October month in 2019. Several scientists have reported that the bustling of firecrackers during the light festival celebration enhances the concentration of particulate matter by manifolds than the background concentration (Yadav et al., 2022; Zhang et al., 2010; Zhao et al., 2014). Thus, during the post-monsoon season, anthropogenic activities like burning stubble (agricultural waste) in the fields of western Uttar Pradesh, Punjab, and Haryana, as well as fireworks display during Diwali festival coupled with low wind speed and geographic surrounding of Delhi with Deccan Plateau in south and Himalayas in the north enables entrapment of high concentration of PM near ground level (Bangar et al., 2021; Perrino et al., 2011; Rai et al., 2020).

$PM_{2.5}$:PM_{10} Ratios over UTS and UBS were also offered (Fig. 4a–h) to present a clearer picture of variation in PM_{10} and $PM_{2.5}$ concentration. It was


January 2019
January 2020
May 2019
May 2020
August 2019
August 2020
November 2019
November 2020
Concentration (µg/m³)
Ratio (PM2.5 : PM10)
Hours
a
b
c
d
e
f
g
h
PM2.5 Traffic
PM2.5 Background
PM10 Traffic
PM10 Background
Ratio Traffic
Ratio Background

◂**Fig. 4** Diurnal variation in PM_{10} and $PM_{2.5}$ concentrations for 2019 and 2020

observed that winter month (January) was dominated by $PM_{2.5}$ concentration. One of the dominant reasons could be the stable atmospheric conditions prevalent during the winter months. As a result of low atmospheric temperature and low wind speed, the atmosphere becomes stagnant which in turn traps the pollutants emitted locally (Payra et al., 2016; Kanawade et al., 2020). High relative humidity was also observed in winters which aggravate the secondary formation process (Singh et al., 2020).

Summer month (May) was dominated by PM_{10} concentrations. During the summer, high wind speed events accompanied with dust are common over Delhi and its surrounding regions, causing enormous suspensions of dry and loose soil dust (Trivedi et al., 2014). Higher temperatures result in more turbulence, which aggravates surface dust re-suspension and increases particulate matter concentration (Sharma et al., 2022). Additionally, local emission sources majorly vehicular and industrial emissions along with road dust resuspension add-up to PM_{10} concentration (CPCB report, 2010; Sharma et al., 2014; Jain et al., 2018). These appears to be a governing phenomenon for the development and domination of particulate matter (PM_{10}) over Delhi.

In addition, the regional-scale transport of particulate matter, particularly dust storms from nearby locations, influence the particulate matter concentration in the atmosphere of Delhi. Singh et al. (2021) reported that Delhi experiences wind predominantly from west-northwest direction along with north-westerly and west-southwest direction. The pre-dominant wind speed falls within the range of 1.9 to 2.4 m/s. Similar results have been document in earlier studies, where the predominant wind direction was northwest, west–northwest directions during pre-monsoon season (Deshmukh et al., 2012; Garg & Gupta, 2020; Mandal et al., 2016; Sharma et al., 2022; Srivastava et al., 2008). In the beginning of March, a change in wind direction from north-western to south-western delivers heat waves known as Loo' from the desolate region of Rajasthan (Kumar et al., 2021). It is further reported by Sethi et al. (2021) that wind blowing from west to east direction may be a potential reason for dust particle transport over the IGP region (including Delhi). Therefore, all these factors combined together are probable reasons for higher PM_{10} concentration over Delhi in summer month.

Table 2 A numerical summary of PM_{10} concentration and meteorological parameters for 2019 and 2020

Month	*PM_{10} concentration (in µg/m³)*		*Meteorological parameters*							
	Urban-traffic stations—UTS	*Urban-background stations—UBS*	*Ambient Temperature in °C (Max. – Min.)*		*Wind Speed in m/sec (Max. – Min.)*		*Relative Humidity in % (Max.-Min.)*		*Solar Radiation in Wt/m² (Max. – Min.)*	
	(Mean ± SD)	*(Mean ± SD)*	*UTS*	*UBS*	*UTS*	*UBS*	*UTS*	*UBS*	*UTS*	*UBS*
2019										
January	301.91 ± 74.74	312.61 ± 64.45	19.38–7.61	20.44–9.70	1.70–0.61	1.20–0.59	63.12–33.94	77.18–42.82	351.11–6.42	211.75–6.09
May	264.56 ± 41.73	253.54 ± 36.83	39.37–26.26	39.55–27.24	1.93–0.61	1.38–0.60	33.21–13.94	47.76–22.91	445.21–6.38	361.97–14.58
August	103.04 ± 13.33	96.59 ± 21.05	33.46–26.84	33.48–27.21	1.58–0.79	0.97–0.51	78.61–56.20	89.25–58.71	331.14–5.78	249.69–15.00
November	329.71 ± 37.53	322.07 ± 35.42	29.07–17.98	28.03–18.17	1.20–0.55	0.89–0.51	77.67–44.06	76.96–46.60	283.38–5.03	164.71–10.51
2020										
January	257.29 ± 47.61	239.41 ± 48.12	19.98–10.73	11.81–8.02	1.58–0.60	1.00–0.54	72.79–46.89	84.49–52.10	324.67–4.98	334.36–5.16
May	128.25 ± 21.71	121.21 ± 14.41	40.67–27.95	35.89–26.35	1.88–0.85	1.17–0.64	55.86–27.38	56.68–31.80	433.43–5.13	380.04–16.04
August	56.51 ± 8.27	59.50 ± 10.16	34.11–28.03	34.75–27.35	1.67–0.86	0.99–0.59	83.19–56.07	81.77–60.99	323.63–5.84	244.56–18.83
November	362.32 ± 65.19	330.05 ± 58.42	29.40–15.87	29.72–18.87	1.15–0.44	0.82–0.37	66.49–34.56	71.43–37.73	306.52–6.60	195.41–13.57

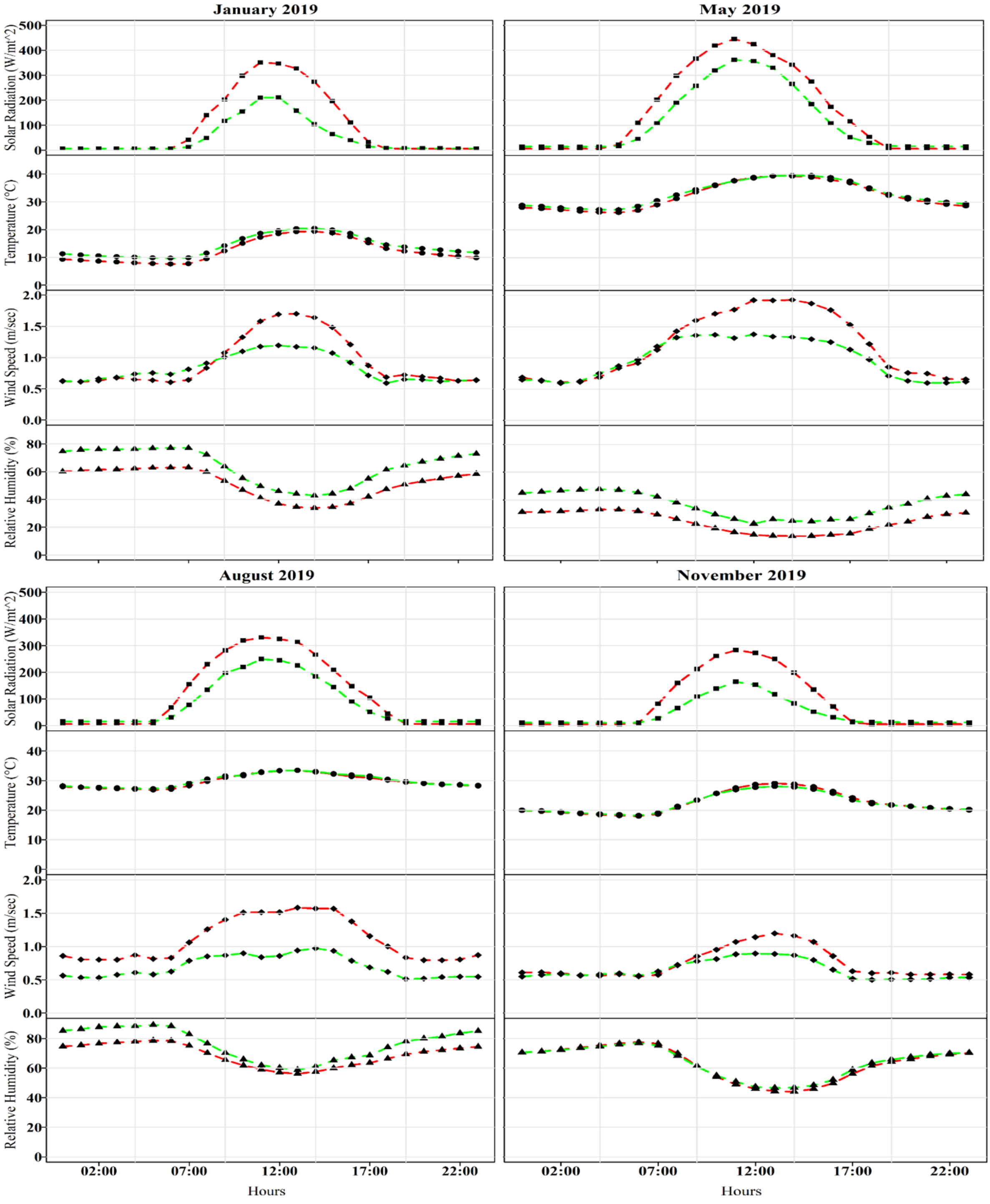


Fig. 5 **a** Diurnal variations in meteorological parameters over traffic (red line) and background (green line) stations for the year 2019. **b** Diurnal variations in meteorological parameters over traffic (red line) and background (green line) stations for the year 2020

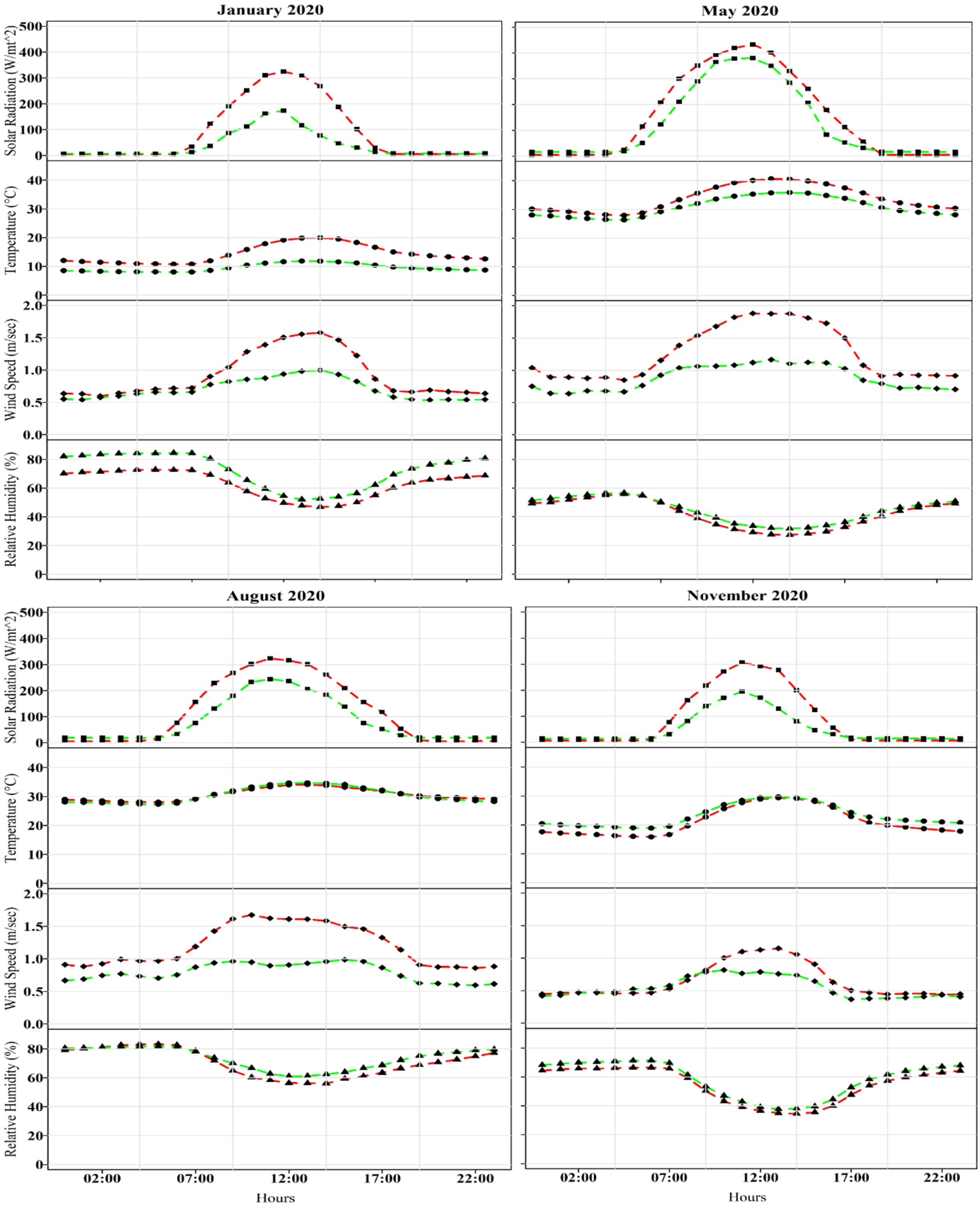


Fig. 5 (continued)

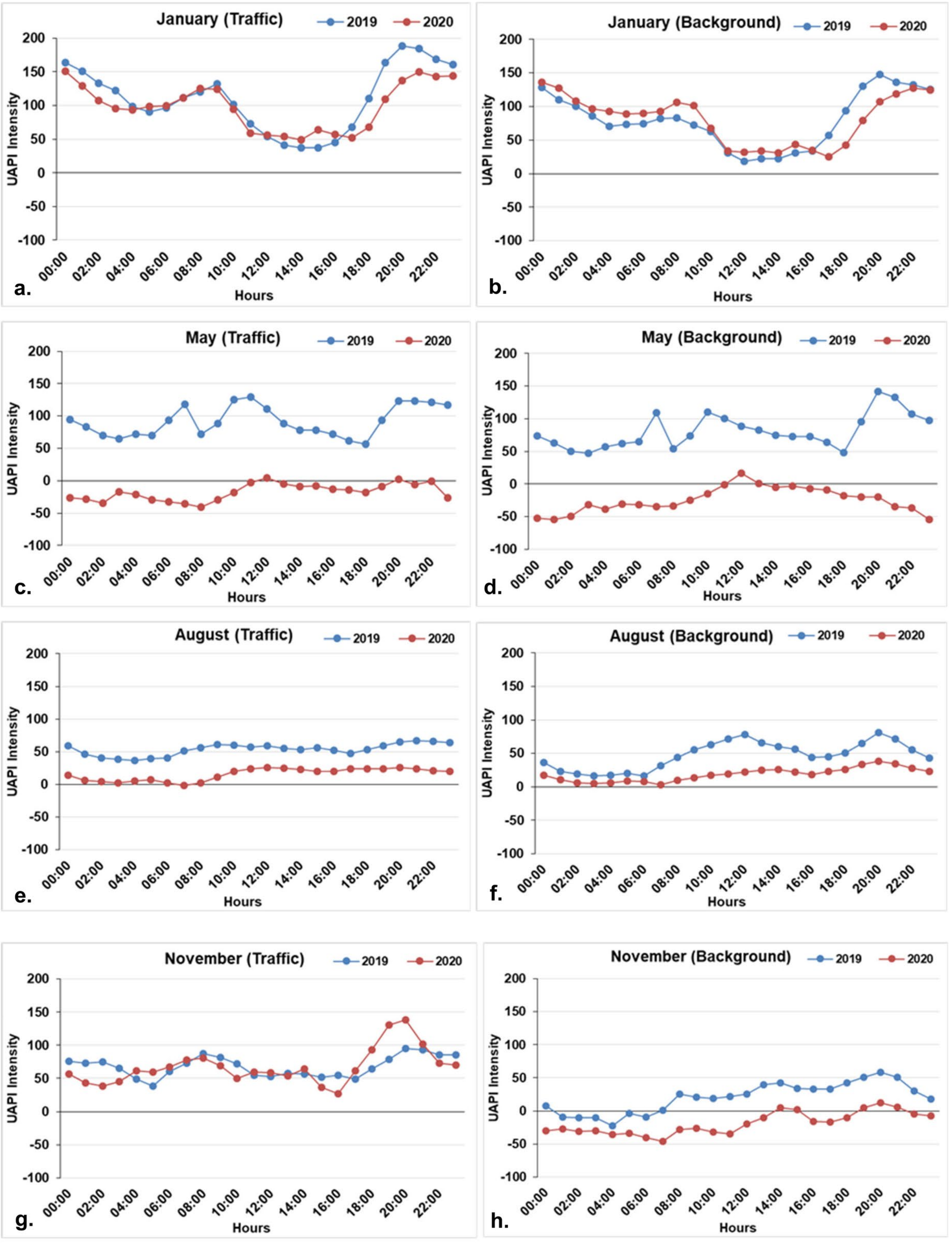


Fig. 6 Diurnal variation in Urban Aerosol Pollution Island (UAPI) intensity over urban traffic and urban background stations for the year 2019 and 2020

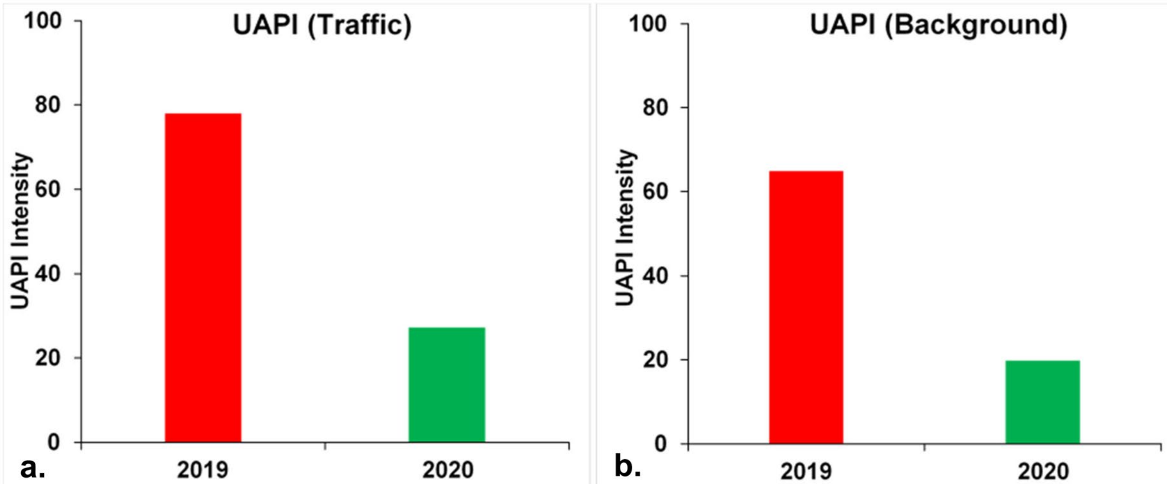


Fig. 7 UAPI intensity over urban traffic and urban background stations for the year 2019 and 2020

To provide an idea for prevailing meteorology during each month, graphs of meteorological parameters are also provided (Fig. 5a, b). Lastly, a month-wise overview of PM_{10} concentrations and the underlying meteorological parameters have been presented in Table 2. Local meteorology of a place plays important role in pollutant dispersion and secondary pollutants formation processes. It also determines the transport and diffusion of the air pollution cycle (Krishna & Beig, 2018; Trivedi et al., 2014). All meteorological parameters have a significant effect on PM concentration and fluctuations in ambient particle concentration depending on the specific weather and atmospheric regimes prevailing in a specific season or day (Kishcha et al., 2014). As an example, in stable atmosphere with higher relative humidity, the transformation of gas-to-particle increases thereby increasing particulate matter concentration (Mohan & Payra, 2014; Xu et al., 2015) So, it is evident that meteorology influences the concentration of particulate matter. Nevertheless, due to the compounding, diverse, and sometimes contradictory impacts that meteorological parameters may have on the accumulation and dispersion of pollutants, it is impossible to quantify the influence of any one meteorological parameter on PM concentrations with great accuracy (Krishna & Beig, 2018).

Figure 6a–h present a comparison of monthly UAPI intensity over UTS and UBS, for 2019 and 2020. UAPI intensity for 2019 and 2020 exhibits similar fluctuations from January with almost identical values. A noteworthy separation in the trend lines appeared in May. For August, the separation between the trend lines of the year 2019 and 2020 was reduced in comparison to the month of May. Overall, the UAPI intensity underwent a massive down surge in May with values remaining below zero. This shows that the implementation and removal of lockdown restriction drastically affected PM_{10} concentration over Delhi. The highest UAPI value was calculated to be 188.37 for January 2019 over UTS, while the lowest value was −54.63 for May 2020 over UBS.

Figure 7a and b represent the annual averaged UAPI intensity over UTS and UBS for 2019 and 2020, respectively. In both stations, the UAPI intensity underwent a down surge and the intensity was higher in 2019 as compared to 2020. UTS experienced a decrease of 65.07% while UBS experienced a decrease of 69.50%. This indicates that the air quality improved over the study area for the year 2020. Similar results describing improvement air quality of Delhi was also reported in other literatures such as Shrestha et al. (2020), Singh and Chauhan (2020), and Soni et al. (2021).

Conclusion

The sudden emergence of global human health emergency brought forth by the novel coronavirus (COVID-19) outbreak presented challenges for the global economy as well as medical and governmental responses. Lockdown implemented to control this situation led to a major downfall in the national economy. Unexpectedly, this cessation period of anthropogenic activities resulted in a cleaner atmosphere across different regions of the world.

This paper attempts to assess the annual, monthly, daily, and hourly variability in particulate matter concentration (particularly PM_{10}) over the Delhi metropolis from January 2019 to December 2020 assuming the metropolis as Urban Aerosol Pollution Island (UAPI). We have summarized the major results of the present research work below:

- PM_{10} concentrations underwent a massive down surge during May 2020.
- January (winter month) was dominated by $PM_{2.5}$ concentrations while May (summer month) was dominated by PM_{10} concentrations.
- For the year 2020, the months of January and November exhibits almost similar variations in UAPI Intensity as observed in 2019.
- UAPI intensity was lower in 2020 as compared to 2019 for May and August, the period for which the lockdown was implemented.
- The UAPI index declined from 77.92 in 2019 to 27.22 in 2020 in traffic-affected areas and 64.91 in 2019 to 19.80 in 2020 in background areas.

Daily anthropogenic activities not only affect the immediate surroundings but also the far-away regions. The findings of this research will assist policy makers and the public in making more informed decisions regarding their daily activities. The results further suggest that organizations need to consider the phenomenon of UAPI while targeting the problem of air pollution. Alleviation of air pollution and educating the public about its health impacts need to be prioritized to promote sustainability and public health in the long run.

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Declarations

Competing interests The authors declare no competing interests.

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