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ORIGINAL PAPER

Variation in Air Quality over Delhi Region: A Comparative Study for 2019 and 2020

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Abstract

Air quality of highly industrialized cities has shown enhanced potential for adverse impacts upon environment and human health. Spread of the COVID-19 in people suffering from some ailment is one of the examples. Meanwhile, complete and partial lockdown were imposed, nationwide, throughout the globe. This study portrays the spatio-temporal variations of atmospheric pollutants over eight regions in National Capital Territory (NCT) Delhi, India, during 2019–2020. It focusses on the entire year with special emphasis on four phases of lockdown and unlock with varying restrictions. As compared to 2019, the results show decrease in relative percent by for fine particulate matters (~ 11.6%), oxides of nitrogen (~ 7%), oxides of sulfur (~ 3.7%), ozone (~ 7.7%), carbon monoxide (~ 20.7%), benzene (~ 11%) and toluene (~ 14%). It was found that strict lockdown phase-I had major contribution to this change. Toluene:Benzene ratios for summer coinciding with strict lockdown confirmed non-operating stationary sources. Later phases were provided with relaxation in certain sectors (mainly vehicular mobility and industrial sector) accompanied with various meteorological impacts, hence did not show much variations. After unlock-IV, anthropogenic activities were found to be accelerated to meet the halted economic demands. Meanwhile, during winter season, biogenic emissions and meteorological factors together affect the air quality in India, aiding air dispersion inhibition due to which the pollutants level showed immediate rise. Restricted human activities prevailing during the lockdown and unlock phases proved to be beneficial in terms of stumping the emission of pollutants into the ambient environment proving that the imposed lockdown healed the environment temporarily.

Keywords Spatio-temporal variation · Air quality · Lockdown effects · $PM_{2.5}$

1 Introduction

COVID-19 evolved out as a historic episode in the age of sophistication, which exceptionally impacted the globe. Due to this, the imposed 'lockdown' measure halted the mobility of people and goods which led to slumped socio-economic development; however, its extended consequences played a significant part benefitting the environment. Post lockdown, the prevailing socio-economic trough provided a short span of chance to the nature to re-bloom, hence, reminding of occurrence of possibility for its recovery from what it had been undergoing across time.

In India, March 21, 2020 was marked as the first day of lockdown (consensus lockdown) which proceeded with complete and partial phases of lockdown (Table 1). This enforcement allowed restricted movement of goods and people as per their priority and/or urgency. Later the Government of India permitted to exit through guarded unlock phases aiming to resume certain activities (such as limited social, academic, religious and political gatherings, and inter- and intra-state movement) restricted during lockdown.

Different research groups across the world tried to assess the effect of initial lockdown phase(s) and reduction in the anthropogenic activities on the levels of selective chemical species. Significant decline for NO_2 levels was observed in the UK (~ 42%) (Lee et al. 2020), China (~ 60%) (Shi and Brasseur 2020) and Spain (~ 56%) (Baldasano 2020). Kang et al. (2020) studied the temporal variation for $PM_{2.5}$ concentrations during lockdown period (February and March, 2020) in China (~ 16%) and South Korea (~ 10%) and found that the reduction in the pollutants' emissions was not sustained because of resurgence of transportation, energy and economic systems. The observed comparative increase in

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Table 1 Air Quality Monitoring Stations (twenty-four) of CPCB, New Delhi chosen for present study

Regions	Monitoring stations	Regions	Monitoring stations
ND	Alipur	CD	ITO
	Narela		Pusa
	North Campus DU		Shadipur
ED	IHBAS, Dilshad garden	NW	Ashok Vihar
	Okhla Phase-2		Jahangirpuri
	Vivek Vihar		Wazirpur
SD	Jawaharlal Nehru Stadium	SW	Dwarka-Sector 8
	Nehru Nagar		IGI Airport (T3)
	Sirifort		R K Puram
	Sri Aurobindo		Sri Aurobindo Marg
WD	Mundka	NE	East Arjun Nagar
	Punjabi Bagh		Sonia Vihar

the levels was found to be affected by varying meteorological conditions, such as lowered surface wind dispersion and increased humidity. In Hong Kong (China), ambient emissions of $PM_{2.5}$, CO, NO_2 and SO_2 were reduced by 7%, 7%, 8% and 14%, respectively, during initial phase of lockdown as compared to the average data for 2019 (Huang et al. 2020). In Sao Paulo, Brazil, monitoring stations sited at urban roads recorded relative reduction of ~ 65% in NO_x concentration, for the April month of 2015–2019 (Nakada and Urban 2020). A short-term study for ten days before and after lockdown in Morocco noted a considerable decline of about 49%, 96% and 2% for the levels of SO_2, NO_2 and temperature (Otmani et al. 2020). Liu et al. (2020) has reported the sector-specific contributions, such as ground transportation emissions (40%), power generation (22%), various industrial emissions (17%), aviation emissions (13%), shipping emissions (6%), and commercial and residential buildings (~ 3%), in emanating CO_2 in ambient atmosphere across the globe. Sanap (2021) studied satellite derived aerosol optical depth (AOD) datasets using Moderate Resolution Imaging Spectroradiometer (MODIS) and the Modern Era Retrospective analysis for Research and Applications (MERRA-2), and reported initiation of decline in AOD values over China from January in backdrop of high aerosol loading over rest of the global aerosol hotspots by the virtue of emergence of COVID-19 in the beginning of 2020. Enhanced aerosol loading was identified over the Amazon River basin, regions of South America, parts of Mexico, West Central Africa and SE Asia during peak months of lockdown. The observed significant aerosol loading was inferred due to wildfire events in these regions since there were controlled anthropogenic emissions. Reduction in aerosol loading over majority of the aerosol hotspots was observed from mid-March/April 2020 with highest percentage reduction in the month of May.

Research groups in India also observed a similar trend. Vadrevu et al. (2020) reported pronounced decline (43–62%) in NO_2 levels [both ground station as well as satellite (TROPOMI-NO_2) data] for forty-one major cities. Mahato et al. (2020) reported negative variation in levels of NO_2 (52.68%) and CO (30.35%) between lockdown and pre-lockdown phases in National Capital Territory (NCT) of Delhi. Jain and Sharma (2020) and Mor et al. (2021) observed remarkable rise of ~ 7% and ~ 39% in the levels of ozone during the first phase of lockdown over Delhi and Chandigarh, respectively due to decrease in NO_x emissions which promotes ozone formation. Significant reduction in the ambient pollutants' (particulate matter, trace gases and certain Volatile Organic Compounds) level, especially, for the pre- and initial phases of lockdown over Indian cities has been reported by various research groups (Kotnala et al. 2020 and Srivastava et al. 2020). Another study by Garg et al. (2021) reported decline in the levels of ten pollutants as well as AQI over five cities of National Capital Region (NCR) of India during initial lockdown phase as compared to three weeks prior to lockdown declaration. The maximum reduction was observed for NO (60–78%), whereas AQI of Ghaziabad was found to be highly reduced (67.63%) followed by Delhi (61.34%). Crilley et al. (2021) tried to assess the changes in median levels of $PM_{2.5}$, NO_x, NO_2, NO and O_3, in Delhi and Hyderabad during March 1, 2017–April 24, 2020. Further, these quantified results were compared with the results obtained by running boosted regression tree model (a prediction model based on meteorological input). The obtained values differed notably; however, the trend of reduction was similar for both methods.

Certain other studies (Zhen et al. 2017; Sarkodie and Owusu 2020) diagnosed that meteorological factors, such as air pressure, air temperature and relative humidity, possess broader control over the airborne bacterial communities and this, in turn, depends upon the level of atmospheric pollution. The twisted interplay between microbes and atmospheric pollutants, most commonly the oxides of sulfur, nitrogen and carbon, adversely affected the respiratory system (Ichinose et al. 2008). These pollutants along with ozone, particulate matter and VOCs may also induce damage to the cardio-pneumatic as well as immune system (Zoran et al. 2020). Population with such conditions suffered the most with COVID-19 transmission; however, the lockdown duration proved to be intensive measure curbing the then ongoing transmission of COVID-19. The worsened quality of air is potential enough to risk massive health affecting the respiratory system, in particular. Various aromatic hydrocarbons fractions of fine carbonaceous aerosols due to biomass burning (30–38%) and vehicular emissions (32–40%) along with other emission sources contribute to lung cancer risk (Gadi et al. 2019 and Shivani et al. 2019). Despite reduction in the pollutants' level, the air quality steeped down concomitantly with relaxation in the lockdown regulations.

A complete year study is able to reflect the trend of variation in the target parameters as a result of the extent of imposed restrictions in different lockdown and unlock phases. This study aimed at examining the baseline pollution (i.e., lockdown phases with minimal anthropogenic activities) and meteorology for entire years of 2019 and 2020. It projects the assessment of ambient concentrations of fine particulate matter ($PM_{2.5}$), oxides of nitrogen and sulfur, carbon monoxide, ozone, benzene and toluene alongwith variation in meteorological parameters (temperature, precipitation, relative humidity, wind speed and wind direction) during the study period. The study presents the spatio-temporal variations in the criteria air pollutants over the complete NCT of Delhi, India, revealing and comparing their status in the ambient air in the absence of numerous potential sources, before lockdown, during lockdown and unlock phases throughout 2020, and to compare the levels of their concentration with that of previous year 2019.

2 Materials and Methods

2.1 Study area: Topography and General Meteorology

The NCT of Delhi has been the most agglomerated, leading megacity of our nation; this lets the crowd of about 1.68 crore in number inhabiting 11,297 person/km^2 as per Census, 2011 (http://census2011.co.in). Being a landlocked city, it attracts more people and opportunities of development from all aspects. It lies at coordinates 28.61 N, 77.23 E and is under influence of its location: south to the Himalayas, south and west to the Indo-Gangetic Plain, north of the heated plains and east to the Thar (desert). The capital city of India exhibits five characteristics seasonal variation over the year which are spring (March to April), summer (May to June), monsoon (July to September), autumn (October and November) and winter (December to February) with average temperature of 20–25 °C, 25–45 °C, 30–35 °C, 20–30 °C, 5–25 °C, respectively, with semi-arid as its overall climatic feature.

2.2 Sampling Sites

Figure 1 shows the eight regions over the NCT of Delhi, namely North Delhi (ND), East Delhi (ED), South Delhi (SD), West Delhi (WD), North-east Delhi (NE), North-west Delhi (NW) and South-west Delhi (SW). The monitoring stations (twenty four) as shown in Table 1 have been focused in this study. These sites are being continuously monitored and real-time updated (online) by the Central Pollution Control Board (CPCB), New Delhi for measurement of various air quality parameters.

2.3 Methodology and Data Analysis

The continuous datasets for levels of ambient fine particulate matter, oxides of nitrogen and sulfur, carbon

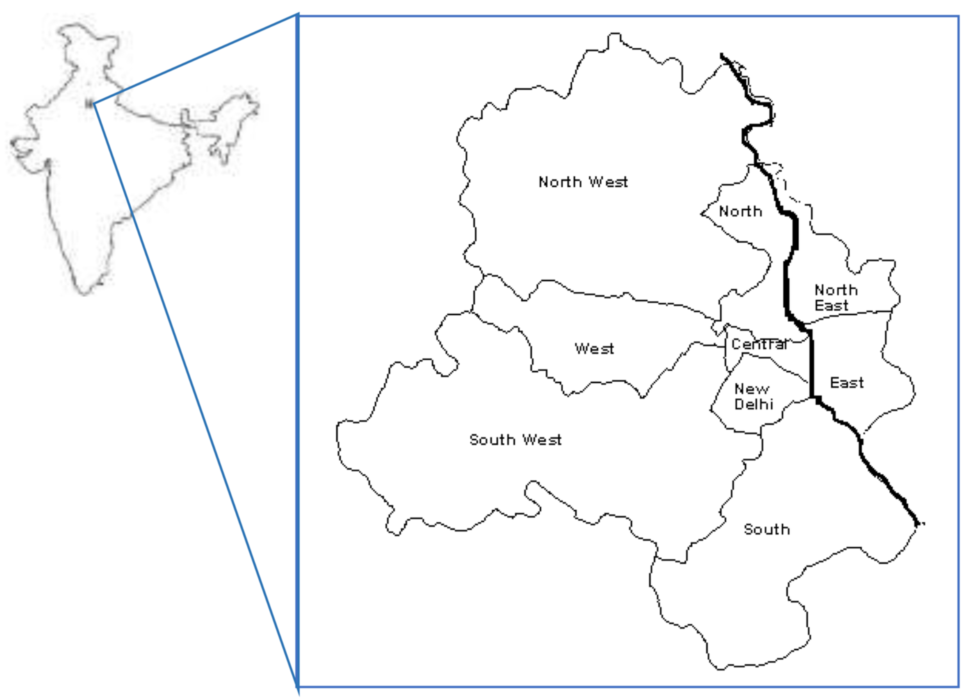


Fig. 1 Map of NCT of Delhi (study area)

monoxide, ozone, benzene and toluene as well as temperature, precipitation, relative humidity, temperature, precipitation, wind speed and wind direction for the duration of January, 2019 to December, 2020 were obtained from the Continuous Ambient Air Quality Monitoring (CAAQM) repository of CPCB, New Delhi, India. The daily concentrations of the criteria pollutants, over the selected sites (based on data availability), were recorded to study the effect of control on activities contributing to their enhanced level in the ambient atmosphere. To obtain quality results, these daily concentration values were evaluated and plotted as their monthly mean instead of retrieving averaged values directly.

In this study, it has been attempted to compare interphase and temporal differences in the pollutants' concentrations for the corresponding duration during both the years, keeping in consideration various lockdown and unlock phases as given in Table 2.

Table 2 List of phases of lockdown and unlock with the corresponding time-interval

Phases		Duration (2020)
Lockdown	I	March 25–April 14
	II	April 15–May 3
	III	May 4–May 17
	IV	May 18–May 31
Unlock with restrictions	I	June 1–30
	II	July 1–31
	III	August 1–31
	IV	September 1–30

3 Results and Discussion

In this study, levels of selected ambient air quality and meteorological parameters during the year 2020 were compared to that of 2019 by considering the monthly mean of 24-h daily data, where January 1–March 24, 2020 marks pre-COVID-19 duration. Table 3 displays relative percentage change observed in the levels of ambient air and meteorological parameters from January, 2020 to December, 2020. The data comparison showed notable reduction in the concentrations of the target pollutants during and after lockdown period.

3.1 Monthly Variations with Lockdown Effect

3.1.1 Variation in $PM_{2.5}$, NO_2 and NO_x

Figure 2a depicts the monthly variation in $PM_{2.5}$ levels over selected zones throughout 2019 and 2020. For the year 2020, maximum relative dip of ~ 23 µg m^{-3} (~ 18%) in the levels was exhibited by NW region; although WD and NW regions reflected quite similar values for the $PM_{2.5}$ concentration (106 ± 1.8 µg m^{-3}). While considering monthly variation during and post-lockdown, a downward graph in terms of relative percent change (~ 47% to ~ 22%) was observed from April to August, irrespective of the daily average data. The comparison between the monthly average values for 2020 with 2019 reveals a similar trend; the difference lies in the comparatively lower values during 2020. Also, as compared to the restricted months (March to September), the later months (October to December) possess ~ 76% positive change in the levels resembling the trend as of previous year. As shown by Figs. 3 and 4, decreased temperature, increased relative humidity and lack in precipitation inhibit

Table 3 Relative percent change in levels of selected parameters during discussed phases (2020) with that of previous year (2019)

Parameters (→)/ Months(↓)	$PM_{2.5}$ (%)	NO_x (%)	NO_2 (%)	SO_2 (%)	CO (%)	O_3 (%)	Benzene (%)	Toluene (%)
Jan	− 25	− 12	− 23	− 18	− 11	− 16	− 26	− 31
Feb	− 3	16	5	6	4	12	12	− 17
Mar	− 32	− 17	− 21	− 6	− 22	− 3	− 33	− 28
Apr	− 47	− 49	− 54	− 6	− 31	− 34	− 50	− 46
May	− 37	− 48	− 50	− 4	− 18	− 51	− 19	− 23
Jun	− 31	− 42	− 41	− 10	− 12	− 55	− 2	− 17
Jul	− 27	− 23	− 33	6	− 18	− 12	43	3
Aug	− 22	− 13	− 12	− 8	− 15	28	93	41
Sep	10	20	− 8	4	− 16	− 2	41	17
Oct	20	57	21	32	13	− 9	− 6	1
Nov	5	32	19	8	15	33	− 42	− 41
Dec	5	27	8	13	19	60	− 33	− 32

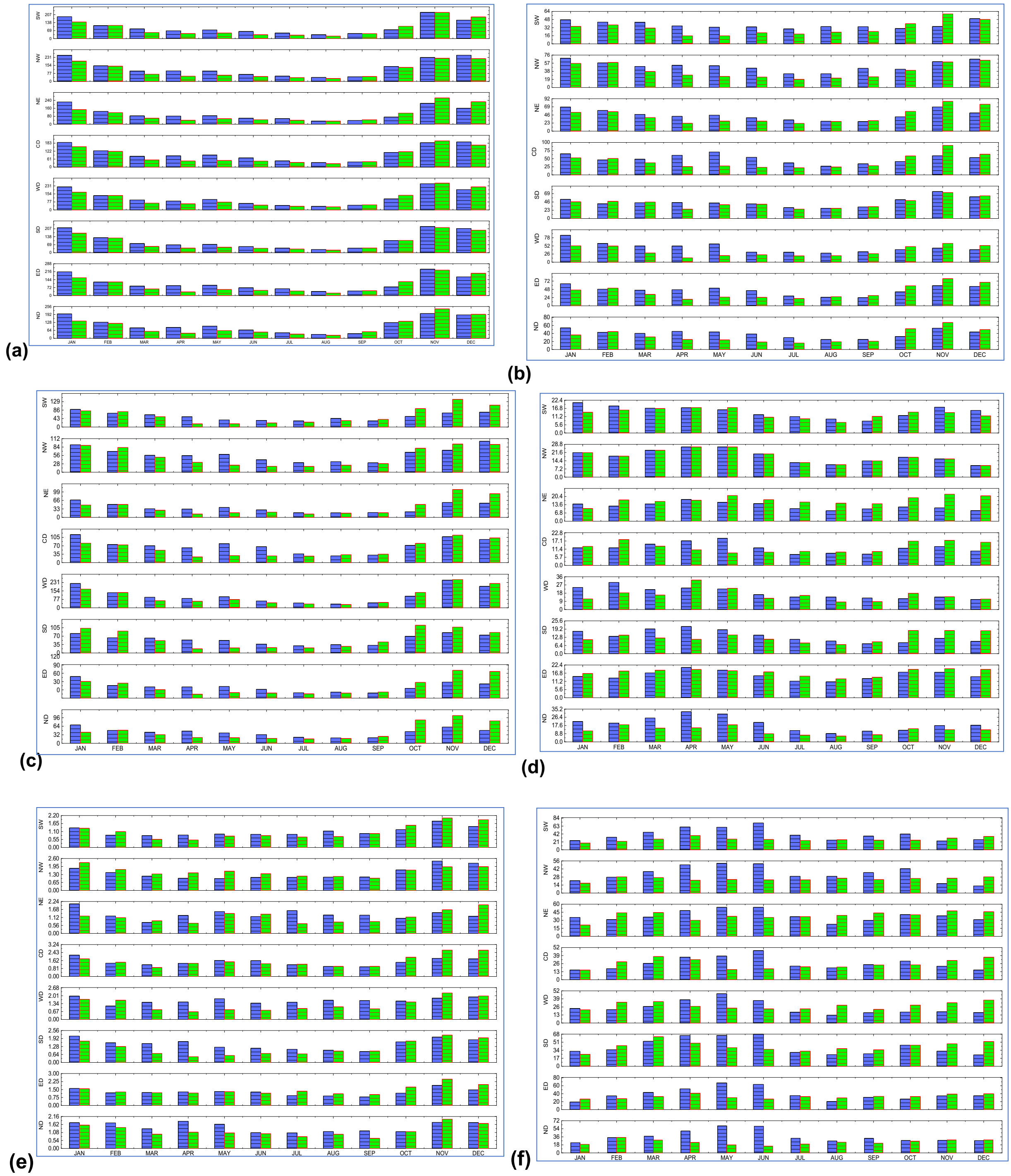


Fig. 2 Variation in levels of the selected pollutants: **a** $PM_{2.5}$ (μg m^{-3}), **b** NO_2 (μg m^{-3}), **c** NO_x (ppb), **d** SO_2 (μg m^{-3}), **e** CO (mg m^{-3}), **f** Ozone (μg m^{-3}), **g** Benzene (μg m^{-3}) and **h** Toluene (μg m^{-3}) during 2019 (blue) and 2020 (green)

the pollutants dispersion in highly motorized city, such as NCT Delhi. Hence, the accumulated concentration of $PM_{2.5}$ during October might have occurred due to lifting up of imposed restrictions apart from meteorological effect. The other possible reason may be the dispersion of pollutants generated from stubble burning activities in the adjacent states of Punjab and Haryana (Shivani et al. 2018).

Quite similar to $PM_{2.5}$ levels, the graph for NO_2 levels (Fig. 2b) for lockdown period reflected a gradual dip (ranging from ~ 54% to ~ 8%) from April to September and tended

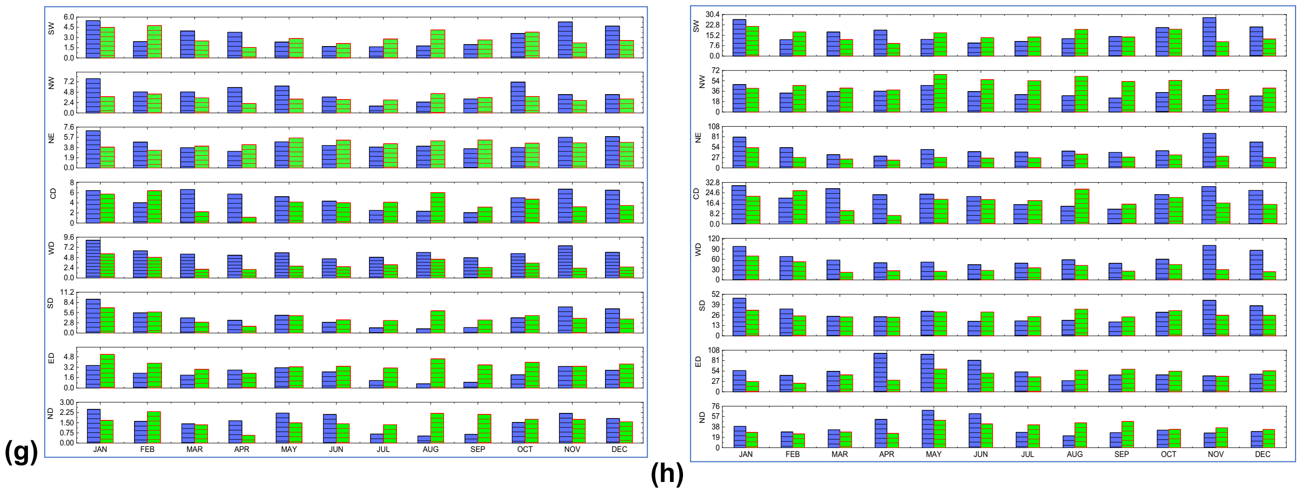


Fig. 2 (continued)

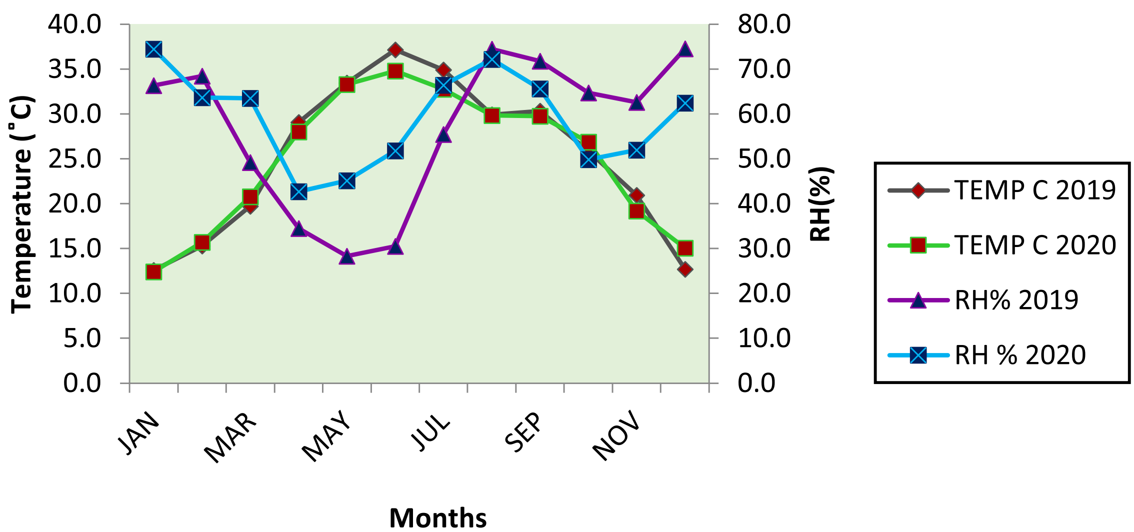


Fig. 3 Graphical representation of trend of variation in monthly average precipitation and relative humidity during 2019 and 2020 over the study area

to increase slightly, thereafter; although the levels for the months of August and September showed a difference of 3 ± 0.6 μg m^{-3}, there had been a similar decreasing trend in the levels during this period. This was in accordance with the results obtained by Garg et al. (2021) for initial phase of lockdown. As per the available data, NW aced over the other regions in terms of monthly average levels during 2019 (57.4 ± 16.3 μg m^{-3}) and 2020 (48.5 ± 22.9 μg m^{-3}), whereas SD region marked a maximum decline of ~ 14.65 μg m^{-3} i.e., ~ 26.4% in terms of the difference and relative change. Exceptionally higher concentrations of NO_x (Fig. 2c) were shown over WD region (averaged to 115 ± 72.65 ppb for the year 2019 and 108 ± 77.14 ppb for the year 2020) for each month. This might be because the monitoring stations in WD region are located adjacent to National Highway—9 and parallel roads and flyovers, (namely Mahatma Gandhi Marg, Mudrika Marg and Punjabi Bagh flyover) hence, are exposed to immense source of traffic emissions. Additionally, temporal-cum-seasonal studies by Mondal et al. (2000) at traffic intersection points support that precipitation effectively attributes to lowered levels of NOx during monsoon season. Increased levels reflected in NW also indicate the role of dense industrial and traffic emissions sources. NE region exhibited the least concentration (37 ± 17.24 ppb) for the year 2019 but turned up for the maximum relative increase of ~ 44% during 2020, whereas

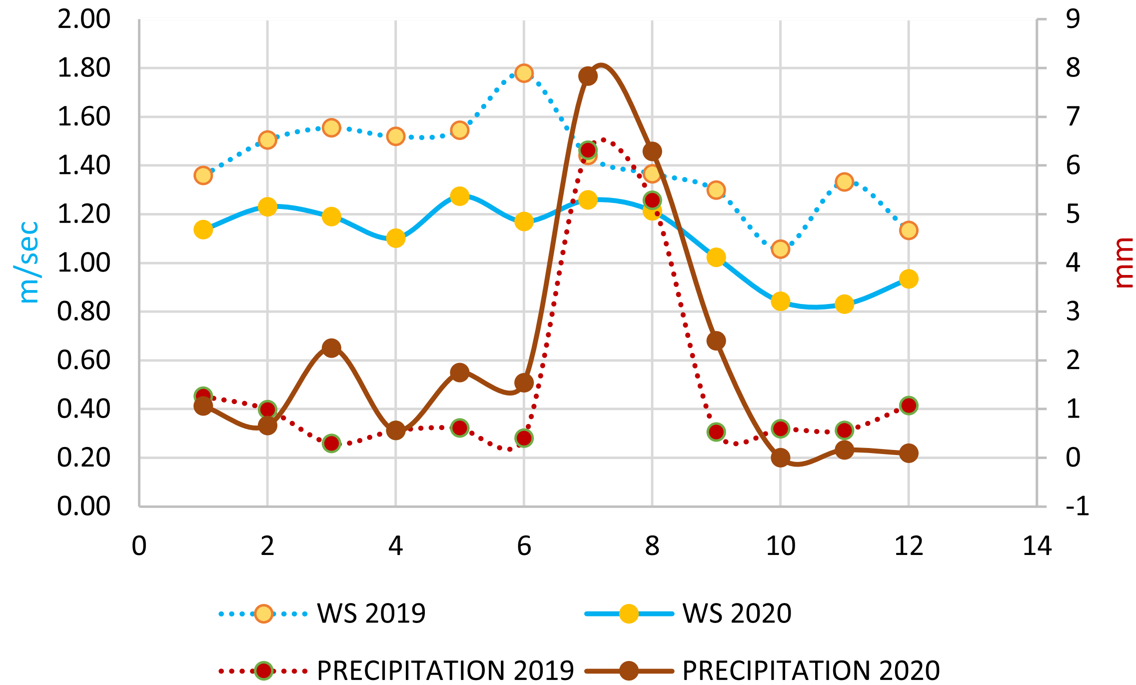


Fig. 4 Graphical representation of trend of variation in wind speed (m/s) and precipitation (mm) during 2019 and 2020 over the study area

CD region recorded the maximum decline of ~ 19% which mainly reflects the lockdown impact. During 2020, the values for April to August dropped markedly (ranging from ~ 22.5 ± 6.6 ppb to ~ 28.9 ± 19.2 ppb); while during lockdown phases of April, May and June marked the highest drop of ~ 49%, ~ 48% and ~ 42%, respectively, in the levels of ambient NO_x concentration.

The gradual rise in the values of $PM_{2.5}$, NO_2 and NO_x levels lies in accordance with the phases of lockdown and unlock. The overall observation depicts an upsurge in the month of October for $PM_{2.5}$, NO_2 and NO_x (by ~ 20%, ~ 21% and ~ 57%, respectively). Also, during unlock phases, in addition to decreased precipitation (Fig. 4), withdrawal of the imposed restrictions to regain the normalcy in the socio-economic dynamics led to sudden hike in their levels. $PM_{2.5}$ dominated over all the selected pollutants in all the regions during November 2020 (post-monsoon). This might have occurred because of agricultural practices (mainly, stubble burning) (Shivani et al. 2018) in the adjacent states, open burning or domestic heating (Breton et al. 2020). The levels took a dip during spring and further decline in the levels during monsoon. NO_x levels originated mainly from traffic sources, dominated, secondarily, over NO_2 in all regions during both the years, except for SD and NE regions, in which NO_2 was comparatively higher in concentration. Considering ND region, Narela representing an industrial site, contributed to the highest concentration for $PM_{2.5}$, NO_x, NO_2 and toluene (2020), although no obvious variation in benzene concentration was observed at any of the monitoring sites. For NO_2 levels, unlike the consistent graph during 2019¸ a decrease was observed after the implementation of lockdown. During monsoon 2020, the level dropped down for all the stations with Narela acing over Alipur. Later, its contribution was totally reversed in 2019 for the similar time frame. $PM_{2.5}$ level shot up with start of unlock, i.e., after monsoon season in2020. Alipur and North Campus, DU (NC-DU) contributed equally during January 2020 to mid-March 2020, while NC-DU equated with Narela during post-lockdown winters; the pattern similar to 2019. Similar trend was observed for NO_x level during both the years but the levels spiked much higher for NC-DU station, with Alipur as the least contributor. From the daily and averaged data considered for each month of both the years, a clear observation for lowered concentration of $PM_{2.5}$ in 2020 was noted. During 2019 and 2020, major contributions in the CD region were due to vehicular emission source such as ITO site followed by Pusa site.

Ambient NO_x levels were contributed by all sites during 2019, but during 2020, Pusa (office and residential site) and Shadipur (traffic site) sites recorded heightened concentration for lockdown phases. During 2019, these dominated the first half, which lasted till the monsoon. In the autumn, the level seemed to rise again, but the 2020 peak took leap over to that of 2019, i.e., during the unlock phases. Trends similar to that of $PM_{2.5}$ were followed during both the years; however, NO_x levels showed uncertain rebounds during each month and phase. Meanwhile, ITO site showed diluted levels during March (possibly due to lockdown) 2020 and monsoon season, but during post-lockdown, it spiked up more than the other sites in CD region. For January–April, value remained the least and similar for both years. But ITO, during post-lockdown, showed the highest values among all; however, it contributed least for benzene and toluene for both the years. Overall, Pusa and Shadipur sites hold the highest concentration values for both the years.

3.1.2 Variation in SO_2

Unlike the other pollutants, SO_2 concentrations are found to be least varying (Fig. 2d). CD region (12.30 ± 3.53 µg m^{-3}) showed the lowest values followed by NE region (~ 14 ± 2.86 µg m^{-3}) for the year 2019. Whereas during 2020, NE and NW contributed the most, approximately by 39% and 28%, respectively. The ambient concentrations were found to be lowered by an average of ~ 2% between June and September, 2020 but the four phases of lockdown (I, II, III and IV) showed more decline. The highest drop of ~ 10% was observed during June, 2020 (i.e., after lockdown was imposed), with significant increase of ~ 32% during October (unlock phase). Also April contributed for the highest concentration (~ 20.1 ± 3.26 µg m^{-3} for 2019; 19 ± 3.03 µg m^{-3} for 2020) while least in August (10.5 ± 3.26 µg m^{-3} for 2019; 9.7 ± 3.03 µg m^{-3} for 2020) to the yearly average.

The spatial variation in SO_2 revealed that NW, ED and NE regions showed comparatively higher values probably due to the reason that these regions mainly comprise residential, traffic, open market and industrial place, thus generating emissions from biomass and fossil fuel combustion. These contributed highly during initial phase of lockdown, but the levels went down considerably by nominal change of 1.30 µg m^{-3}, 0.76 µg m^{-3} and 1.44 µg m^{-3} during these phases and during August as a result of monsoon; however, the levels did not show up during Unlock phases till September, 2020. There was data shortage for SO_2 in ND region, with Alipur being as the sole representative site during 2019. Narela lies beyond the NC-DU site for the year 2020 with lower concentration values during monsoon.

3.1.3 Variation in CO

With slight randomness in the CO levels especially over ED, CD, NE and SW regions, March (2020) exhibited similar trend of decline as in 2019 as shown in Fig. 2e. The impact of lockdown was clearly observed during its initial phase during April with significant reduction of ~ 31% relative to the same duration in 2019. Meanwhile, a relative decrease of ~ 16% was recorded for September 2020 with minimum levels (0.92 ± 0.44 mg m^{-3}). The levels varyingly ranged between 0.92 and 2.15 mg m^{-3} revealing an overall percent change of ~ 7.7% (0.08 ± 0.23 mg m^{-3}) in the levels throughout 2020. The values were apparently higher for 2019, although the trend of variation remained notably similar for both the years. Distinct peaks for increased levels were noted between March and September, 2020 for NW (1.29 ± 0.19 mg m^{-3}), CD (1.19 ± 0.21 mg m^{-3}), and ED (1.19 ± 0.11 mg m^{-3}) regions with relative increase of ~ 7.67%, ~ 9.09% and ~ 15.26%, respectively. During this duration, March and April showed heightened fall in the levels of CO as compared to that of 2019. This might have been favored with increase in solar flux and temperature supporting the CO formation due to oxidation of volatile organic compounds (Ghahremanloo et al. 2021). These conditions also favor increased OH which reacts with CO and in turn lowers the value again. This may be responsible for very minute raise observed thereafter during summer. A clear decline in percent change was observed between restricted months of March and September, 2020 (range: 12–31%) than that of 2019. ED and NW regions majorly encompass industrial and residential areas apart from the inter-state bus terminal in ED region as the prominent sources of pollutant emission. ITO monitoring site in CD region receives emissions from the traffic junctions and flyover. Together, all these contribute to appreciably higher levels of pollutants. The graph showed rise in concentration during winters again after monsoon period due to increased anthropogenic activities and increased biogenic emissions due to domestic fuel combustion for cooking and heating and garbage burning.

3.1.4 Variation in Ozone

Despite substantial increase in peak height for tropospheric ozone in certain regions, the overall value for average concentrations throughout the year 2020 (30.4 ± 37.0 µg m^{-3}) was computed to be lower than that of 2019 (35.0 ± 38.3 µg m^{-3}). It has been noted that, during day time, strong updrafts by wind transport trace gases from surface to upper troposphere, while downward convective fluxes transport upper tropospheric air into the lower height. These exchange processes are frequent in summer and may influence tropospheric ozone concentrations (Yerramsetti et al. 2013). Studies have found that oxides of nitrogen as well as volatile organic compounds play crucial role in formation and destruction of tropospheric ozone (Tiwari and Agrawal 2018; Tadic et al. 2020). In the present findings, NO_x levels support the variation in ozone levels.

Initially, with high stringency in lockdown, the levels went comparatively higher during March (~ 37.0 ± 10.6 µg m^{-3}). The percent change in mean value during April (− 34%), May (− 51%) and June (− 55%) reflects the withdrawal of selective restrictions during lockdown period, in NCT

Table 4 Toluene:Benzene (T:B) ratio for their monthly (daily average) value during 2019 and 2020

Months (→)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2019	8	9	9	11	11	12	14	12	12	9	9	9
2020	8	7	10	12	10	10	10	9	10	10	9	9

of Delhi. Similar observation has been reported by Garg et al. (2021) for initial phase of lockdown in Delhi and NCR of India. During July, August and October, the recovery in ozone levels was accompanied with resumed strictness with values 26.6 ± 6.3 μg m^{-3}, 29.0 ± 6.4 μg m^{-3} and 31.0 ± 7.7 μg m^{-3}. Later, the level dropped by 2.9 μg m^{-3} during October 2020. Bhardwaj et al. (2018) have mentioned that biomass burning can have impact on ozone build-up in the ambient atmosphere. Also, during winters, poor ozone mixing occurring has been observed due to shallow boundary layer height. Hence, it is justified that the levels during November and December, 2020 were seemingly higher than that of lockdown phase. (Fig. 2f). SD monitoring stations recorded the highest average value of 42.1 ± 10.1 μg m^{-3} for the year 2020. Monthly higher values may be related to the least availed routes of these locations during the year as well as distance of the emission source from the monitoring sites.

3.1.5 Variation in Benzene and Toluene

Benzene and toluene have been found to originate mainly from vehicle exhaust, industrial emission, evaporative loss and biomass burning. According to Breton et al. (2020) and Hamid et al. (2020), concentration of these depends upon the meteorological factors and distance and strength of the emission source. It should be noted that stationary sources would contribute to continuous emission of pollutants, whereas emission from mobile sources would follow the source as well as wind direction, hence would not be emitted and accumulated at any specific location unlike the case of stationary sources.

During 2019, the values of benzene concentration as depicted in Fig. 2g show remarkable peaks for WD (5.98 ± 1.22 μg m^{-3}) and CD (4.8 ± 1.12 μg m^{-3}) regions among all the selected zones, whereas none of the regions showed corresponding higher levels for the year 2020. Here, WD and SW were found to be the regions which recorded significant reductions of ~ 64% and ~ 52% for the months of November and December 2020, respectively with relative increase of ~ 9% during the year for all sites.

For the year 2020, the data calculated for each region averaged to almost similar levels (3.75 ± 0.6 μg m^{-3}) of Benzene except for ND. Meanwhile, an overall increase from 2.38 ± 1.2 μg m^{-3} to 4.61 ± 0.8 μg m^{-3} (~ 93%) was observed in August during 2020 as compared to 2019, whereas a notable reduction of 2.0 μg m^{-3} (i.e., ~ 50%), 2.2 μg m^{-3} (~ 42%) and 1.6 μg m^{-3} (~ 33%) was observed during April, November and December, respectively. Thus, an overall fall was observed during initial phases of lockdown during March and April, followed by gradual rise till August 2020, after which the graph descended till the end of 2020. The peaks were also found to be prominent for the winter months of January and February, 2020, i.e., during pre-lockdown period which is supported by the then lowered temperature which traps its dispersion, thus inhibiting the dilution in its levels.

As compared to other regions, the monthly averaged value was found to be the highest for Toluene in NW region (49.4 ± 9.3 μg m^{-3}) during 2020 with least value represented by SW region (15.1 ± 4.0 μg m^{-3}). With progression of lockdown up to Unlock-III (i.e., April to October), an increasing trend was observed for NW (54.8 ± 9.3 μg m^{-3}), ED (48.6 ± 11.9 μg m^{-3}) and ND (42.6 ± 8.5 μg m^{-3}) region. Apart from this, a major decrease in the mean concentration values was computed to be the maximum for the months of April (~ 46%), November (~ 41%) and December (~ 32%) during 2020. An overall decrease had been noted in the first half of the year 2020 which marks the lockdown effect (Fig. 2h).

The peaks for benzene and toluene concentration dipped down as lockdown started (i.e., during March and April, 2020), but these significantly ascended from June to August, 2020. At the same time, the reason for the fall in the levels during November and December, 2020 lies in the corresponding concentrations during 2019, which were considerably higher across WD, NW and SW regions due to the location of monitoring stations adjacent to National Highway, parallel roads and flyovers, and industrial areas. Same applies to the CD region also. The overall reduction in the toluene is mainly contributed due to improvement in the relative levels in WD (− 71%), NE (− 63%), SW (− 54%), CD (− 43%) and SD (− 37%) regions.

In ND, NW and CD regions, toluene showed distinct peak among other; however, each figure showed a common trend of peak rise during summer (especially during May–June) and the month of November in 2019 and 2020. Higher peaks during winter were recorded for 2019 and 2020, which showed decline during initial phases of lockdown followed by further increase thereafter. During 2020, November and December (post lockdown) reduced levels were observed as compared to October 2020. If analyzed in depth, we find that these were normal values as per the existing situation, actually. The overall trend of rise during October 2020 changed the interpretation superficially. Practically, it indicated the

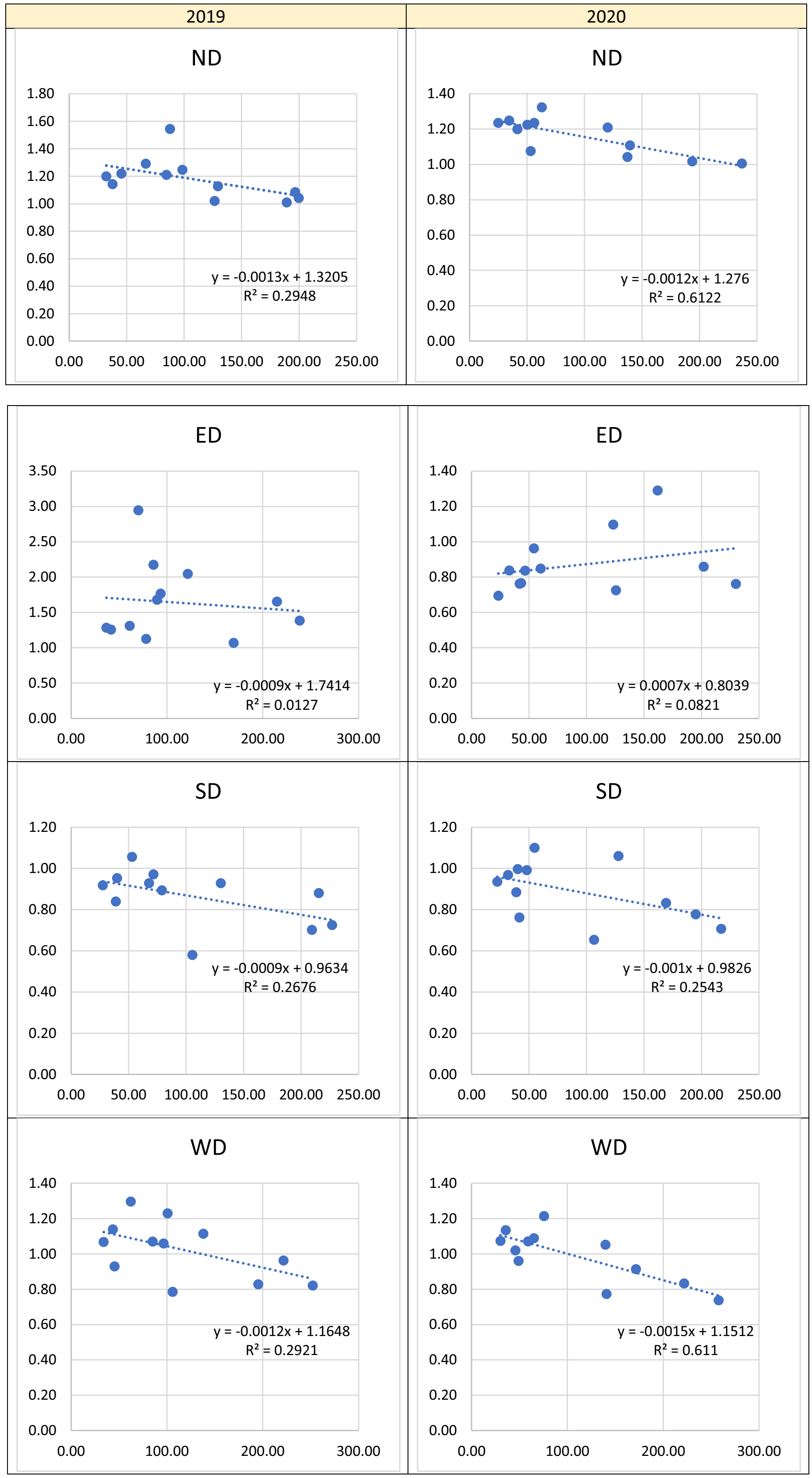
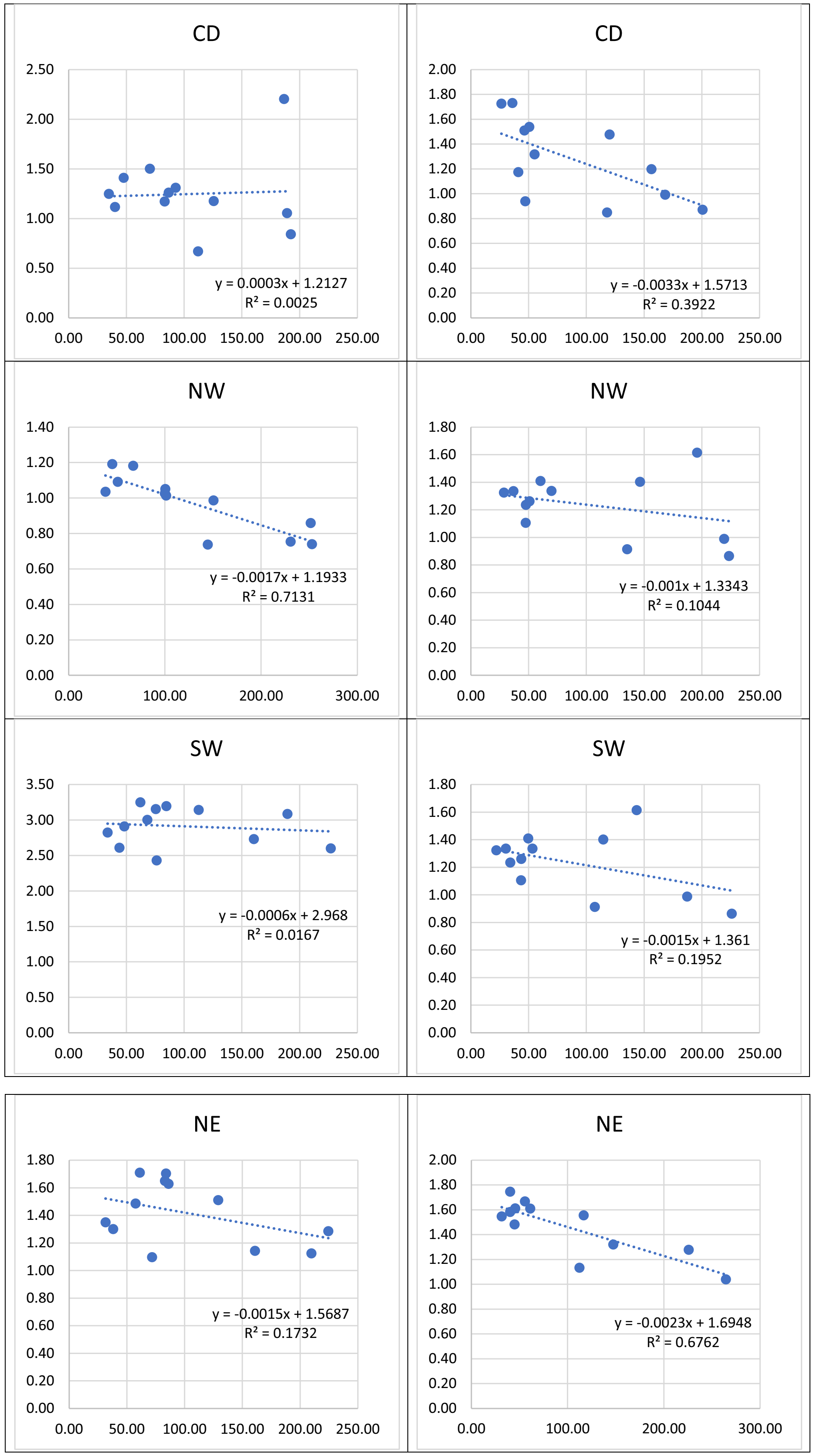


Fig. 5 Correlation between $PM_{2.5}$ and wind speed for 2019 and 2020 over the studied regions

Fig. 5 (continued)



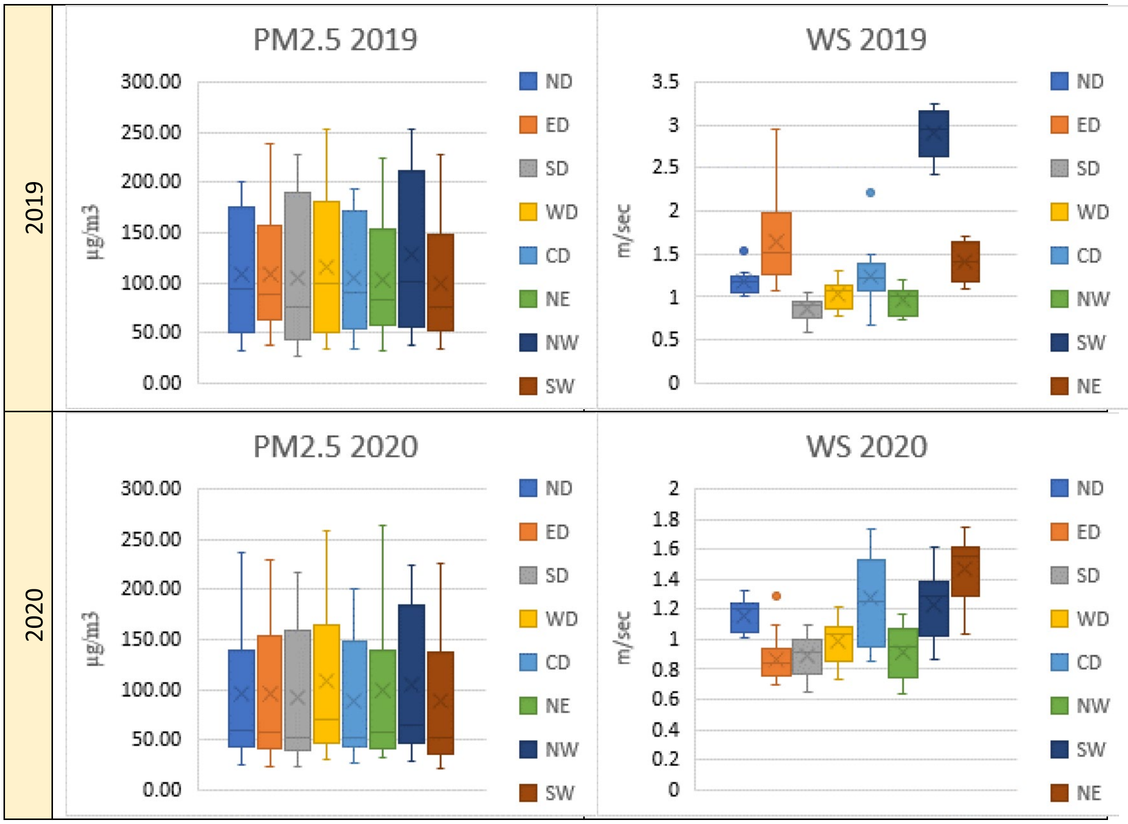


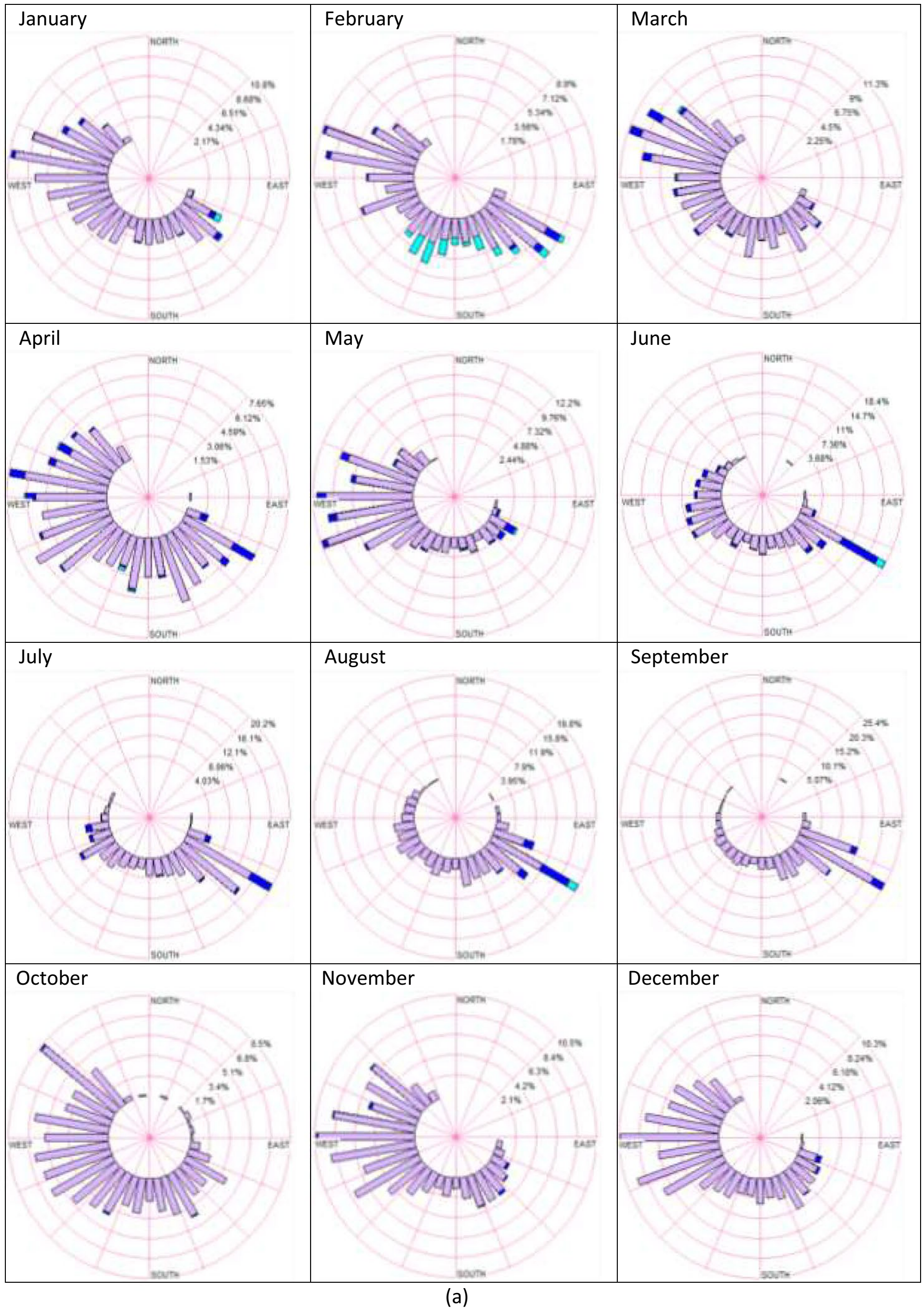
Fig. 6 Box and Whisker plot for $PM_{2.5}$ and wind speed for 2019 and 2020 over the study area

impact of strict lockdown and sudden relief in mobility during October 2020. During winters, due to lessened temperature and solar flux, thus, limited photochemical reactions (Cruz et al. 2020), raised peaks for benzene and toluene were observed. Similarly, the ratio of toluene and benzene (T:B) also gets varied seasonally. This aids in identifying their possible sources of origin (Breton et al. 2020, Hamid et al. 2020). As per the findings of Abtahi et al. (2018) and Sahu et al. (2020), the higher T:B values, as in Table 4, during summer indicate that the sources are mainly stationary in nature (such as industries, biomass burning, etc.) coinciding with lockdown restrictions; whereas the lower ratio during winter (pre- and post-lockdown period) signifies their contribution from mobile (vehicular) sources of emissions. In India, harvesting of crops and burning the farm stubble is usually observed between October and November, which majorly contributes to the T:B ratio during these months. At the same time, the toluene showed major increase in emission during these months, in 2020, in NW region (~9.3%) (major industrial area in NCT of Delhi) as compared to other regions, which might have affected the overall T:B value for 2020.

3.1.6 Variation in Meteorological Parameters

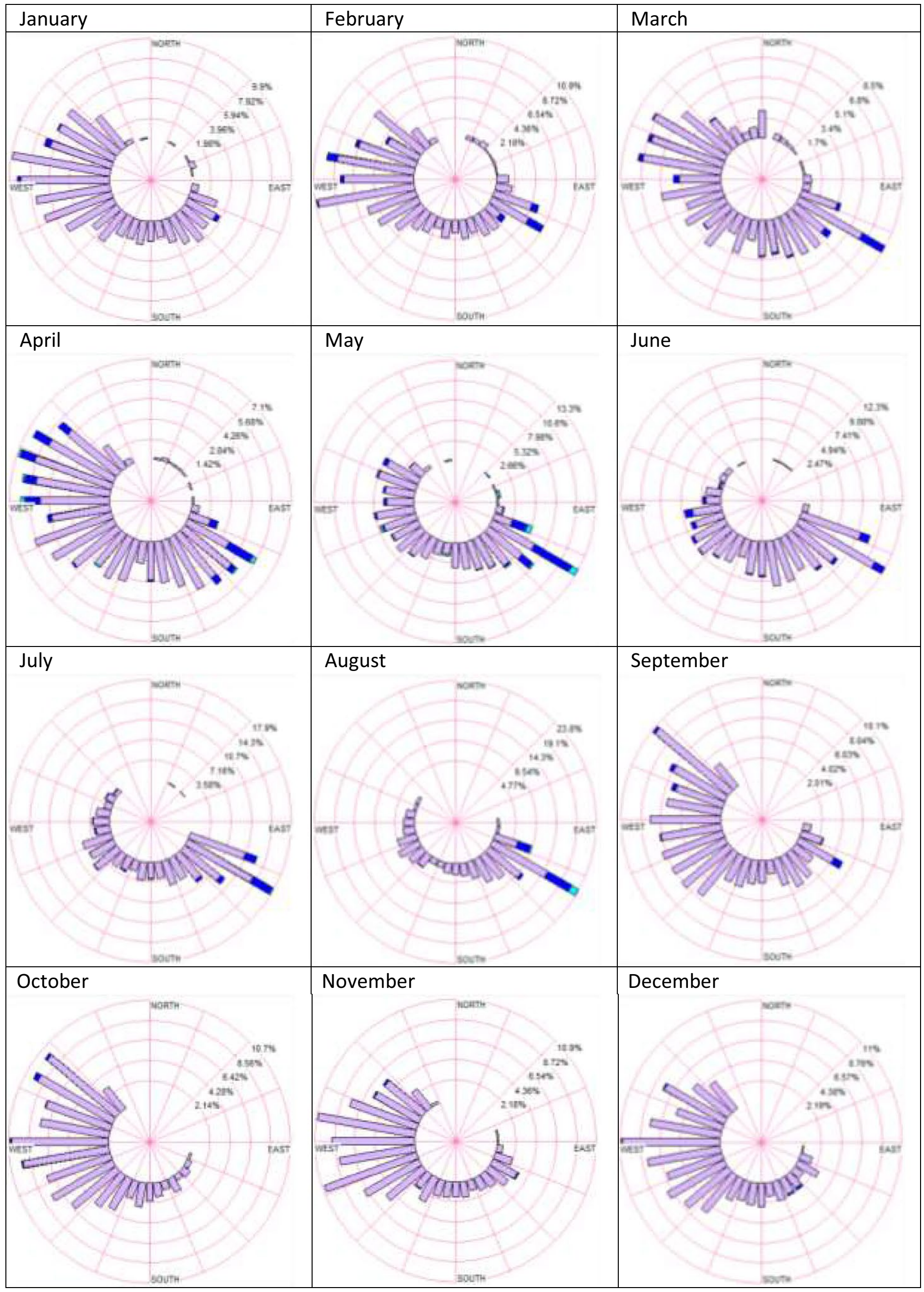
Meteorological parameters (temperature, relative humidity (RH), precipitation, wind speed and wind direction) were assessed to note their role in variation in levels of selected air pollutants. The values for temperature and RH have been found pointing opposite to each-other (Fig. 4). The temperature and RH varied between 12.4–37.2 °C (for 2019) and 12.4–34.8 °C (for 2020), and 42.7–74.5% (for 2019) and 28.3–74.6% (for 2020), respectively. There was insignificant variation in temperature and RH for 2019 and 2020, whereas, RH was found to be higher between March and July during 2020 as compared to 2019. Precipitation observed in 2020 was slightly higher than that of 2019 during March–August (Fig. 4) when increase in RH was also observed. According to the daily average data, the minimum and maximum precipitation recorded for 2019 and 2020 ranged between 0.29–6.31 mm and 0.09–7.83 mm, respectively. Notable impacts of these meteorological parameters were observed on $PM_{2.5}$ and NO_x which showed reduction in levels (as noted in Sect. 3.1.1, Fig. 2). Since it is well established that higher wind speed dilutes the $PM_{2.5}$ levels, it was

Fig. 7 Monthly wind rose plot for **a** 2019 and **b** 2020 for the study area

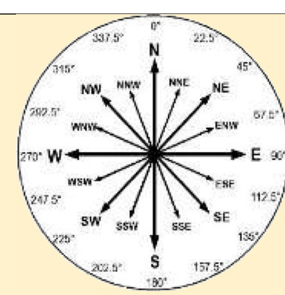


quite interesting to study the overall variation in their levels throughout the year. The calculated average of maximum levels of $PM_{2.5}$ in each of the studied region for 2019 was 226.75 ± 22.02 μg/m^3 and 232.00 ± 20.94 μg/m^3 for 2020. These values differed remarkably from the average of $PM_{2.5}$ mean values of each region (mean$_{2020}$: 96.27 ± 7.25 μg/m^3; mean$_{2019}$: 108.90 ± 8.98 μg/m^3) by 135.73 ± 17.36 in 2020 as compared to 117.85 ± 18.25 in 2019 (Fig. 6). These huge differences might have played vital role in producing narrowed correlations with the wind speed. In the months receiving higher precipitation, the impact of wind speed on dilution of $PM_{2.5}$ was masked as well, which may be inferred from the observed results (Figs. 2 and 4). This can clearly be noted in the correlational studies (between $PM_{2.5}$ and wind speed) (in Fig. 5) for both the years, especially in the region ED, CD and SW in 2019, and ED and NW in 2020. Probable reasons behind this might be the outliers (Fig. 6) for ND (1.55 m/s) and CD (2.21 m/s) in 2019 and ED (1.20 m/s) in 2020, which would have affected the average values for the entire duration of study, but it cannot be neglected for studies to note the trend and impact of each parameter. Unlike mean wind speed, the minimum wind speed (WS$_{min}$) and

Fig. 7 (continued)



Spokes colour in wind rose	Wind speed (m/sec)
(light purple)	upto 2.10
(blue)	2.11 – 3.60
(cyan)	3.61 – 5.70



Wind directions (16)

(b)

Table 5 Linear correlation matrix for selected pollutants and meteorological parameters for 2019 and 2020

2019	$PM_{2.5}$	NO_x	NO_2	SO_2	CO	O_3	Benzene	Toluene	RH	Temp	Preci-pitation	WS
$PM_{2.5}$	1	**0.98**	**0.9**	0.32	**0.97**	− 0.37	**0.91**	**0.8**	0.28	− 0.79	− 0.47	− 0.66
NO_x		1	**0.94**	0.45	**0.94**	− 0.29	**0.96**	**0.84**	0.21	**− 0.82**	− 0.56	− 0.63
NO_2			1	0.69	**0.86**	− 0.01	**0.97**	**0.92**	− 0.08	− 0.66	− 0.45	− 0.45
SO_2				1	0.3	0.59	0.59	0.68	− 0.65	− 0.20	**− 0.70**	0.03
CO					1	0.33	**0.86**	**0.86**	0.22	− 0.66	− 0.39	**− 0.72**
O_3						1	− 0.11	0.15	− 0.94	0.57	− 0.45	0.37
Benzene							1	**0.91**	0.02	**− 0.72**	− 0.64	− 0.62
Toluene								1	− 0.28	− 0.42	− 0.60	− 0.48
RH									1	− 0.56	0.35	− 0.36
Temp										1	0.36	0.46
Preci-pitation											1	0.29
WS												1
2020	$PM_{2.5}$	NO_x	NO_2	SO_2	CO	O_3	Benzene	Toluene	RH	Temp	Preci-pitation	WS
$PM_{2.5}$	1	**0.98**	**0.97**	0.33	**0.98**	0.4	0.16	− 0.13	0.02	**− 0.78**	− 0.55	**− 0.70**
NO_x		1	**0.99**	0.32	**0.96**	0.47	0.2	− 0.1	0.04	**− 0.78**	− 0.56	**− 0.77**
NO_2			1	0.34	**0.95**	0.51	0.18	− 0.13	0.02	**− 0.77**	− 0.57	**− 0.76**
SO_2				1	0.28	0.35	− 0.35	− 0.49	− 0.73	− 0.24	− 0.61	− 0.09
CO					1	0.37	0.19	− 0.02	− 0.2	− 0.68	− 0.50	− 0.68
O_3						1	− 0.37	− 0.56	− 0.2	0.23	0.43	− 0.48
Benzene							1	0.8	0.56	− 0.29	0.16	0.53
Toluene								1	0.35	0.23	0.29	0.23
RH									1	− 0.39	0.43	− 0.03
Temp										1	0.44	0.53
Preci-pitation											1	0.54
WS												1

Correlations higher than 0.7 are highlighted in bold

maximum wind speed (WS_{max}) were observed to vary markedly in CD (WS_{min}: 0.67 m/s), ED (WS_{max}: 2.95 m/s) and SW (WS_{min}: 0.87 m/s) in 2019 (WS_{mean}: 1.25 m/s—CD; 1.64 m/s—ED) during 2019, and ED (WS_{min}: 1.29 m/s), CD (WS_{max}: 1.73 m/s) and NE (WS_{min}: 1.04 m/s) in 2020 (Fig. 6) which might have affected the correlations obtained in Fig. 5, in addition to precipitation. As compared to 2020, the wind speed for each region was found to be more scattered with a high maximum value (discussed above), during 2019.

As per wind speed and wind direction data, wind rose plots were generated and examined for each month of 2019 and 2020 (as shown in Fig. 7). During 2019, February ($WS_{mean} = 1.5$ m/s) and June ($WS_{mean} = 1.5$ m/s) witnessed higher wind speed, whereas May ($WS_{mean} = 1.8$ m/s) was shown to possess higher wind speed during 2020. Monthly wind speed (based on daily average) were found to be more dynamic in 2019, but more calm (< 1.5 m/s) and lesser dynamic in 2020. Differences in WS_{max} and WS_{min} of both the years observed were measured as 0.1 m/s and 0.6 m/s, respectively. Broadly, 16 directions (Fig. 7) were focused to assess the wind direction during the course of study. For 2019, wind speed was found to be higher (3.6–5.7 m/s) than usual when the direction lied between west–southwest (WSW) and east–south-east (ESE). Wind speed between 0.5 and 3.6 m/s was shown to be incoming from north–north-west (NNW) to east–south-east (ESE) most of the times. The observed wind direction for both years differed slightly between January to June and September; rest of the months were shown to have almost similar wind direction. It was found that westerly winds dominated throughout the year, except June to September and May to August in 2019 and 2020, respectively. During these months, for more than 30% of the time, the wind direction (source) pointed toward eastern direction (mainly, south-east). As per Figs. 4 and 7, this was identified as the period when other meteorological parameters (temperature, RH, precipitation) also varied. Impact of these meteorological parameters varied for different air pollutants' levels in each zone which probably is attributable to local sources of emissions.

3.2 Statistical Analysis

3.2.1 Correlations Between Variables

The correlations between the selected pollutants at the studied monitoring stations for 2019 have been shown in Table 5 and for the pre-, during and post-lockdown period, during 2020, in Table 5. The monthly average level of $PM_{2.5}$ correlates highly with that of oxides of nitrogen (NO_2: $r_{2019} = 0.9$, $r_{2020} = 0.97$; NO_x: $r_{2019} = 0.98$, $r_{2020} = 0.98$). SO_2 levels did not show any variation in the annual average value. It also showed no significant correlation with other pollutants during both the years. CO highly correlates with $PM_{2.5}$ ($r_{2019} = 0.97$, $r_{2020} = 0.98$), NO_2 ($r_{2019} = 0.86$, $r_{2020} = 0.95$) as well as NO_x ($r_{2019} = 0.94$, $r_{2020} = 0.96$) indicating common source of origin for major portion of the year (2020). Benzene and toluene showed good correlation ($r_{2019} = 0.91$, $r_{2020} = 0.80$) depicting, possibly, common source of generation; but these did not correlate well with other pollutants. It was found that benzene and toluene highly correlated with $PM_{2.5}$, NO_x, NO_2 and CO during previous year. Moderate correlation was shown by ozone with that of $PM_{2.5}$ ($r = 0.40$), NO_2 ($r = 0.51$) and NO_x ($r = 0.47$) for 2020.

In the present study, correlation between temperature and RH was found to be less inverse in 2020 ($r = 0.39$) as compared to 2019 ($r = 0.56$). This may not be significant because of the imposed restriction during lockdown phases as shown in the Table 5. As a result, when compared to that of average data of 2019, the lesser positive correlation of ozone with temperature was observed in 2020. However, CO and O_3 showed insignificant negative correlation with respect to RH in 2020. Meanwhile, SO_2 significantly correlated with O_3, benzene, toluene, RH, temperature and precipitation (*r* ranging between 0.59 and 0.7). RH–temperature and RH–WS correlated negatively in both years; however, RH–precipitation, temperature–precipitation, temperature–WS and precipitation–WS were observed to be positively correlated. The obtained results imply that restriction on transportation and industrial activities played a major part in reducing the pollutant load in the ambient air in addition to roles of meteorological parameters.

4 Conclusion

Many contemporary research works for the first two phases of the lockdown have been carried out globally utilizing the ground data, satellite data as well as prediction models, which figured out almost similar trend of variations for the levels of ambient air pollutants. This study gives an understanding on the trend of variations in the air pollutants with meteorological parameters due to limited activities during strict and partial lockdown phases. The obtained results varied spatially and seasonally, and also according to stringency imposed during certain phases, as well. Mobility restrictions due to COVID-19, provided the experimental ‘control’ data for comparison with usual ambient levels of the air pollutants. A prominent downshift in the curves of the studied pollutants from anthropogenic sources was noticed during the complete year 2020 as compared to 2019, justifying the impact of complete lockdown phases.

The impact of local, domestic and/or stationary sources of emission during the restricted period was also noticed. High $PM_{2.5}$ levels numerically reduced but actually higher persisting levels in the ambient air is still a matter of serious concern. The assessed results are relatable to both, lockdown and meteorological phenomena. During this period, it was meaningless to perform the source apportionment studies due to restricted anthropogenic activities. The most important finding in this study was the increased anthropogenic emissions after unlock phases, which surpassed the previous year levels as well as degraded the lockdown positive impact on the environment. Hence, it may be concluded that complete inhibition of any industrial or commercial activity for a fixed time span cannot be the effective solution to pollution. This comparative spatial study may further provide information about origin of the pollutants at local level which needs a long-term periodic assessment. Meanwhile, these findings during controlled conditions may help to revise and plan more feasible policy interventions to improve the air quality.

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Data Availability The datasets for the current study can be made available from the authors on reasonable request.

Declarations

Conflict of Interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

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