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Pre-to-post lockdown impact on air quality and the role of environmental factors in spreading the COVID-19 cases - a study from a worst-hit state of India

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Abstract

The present study aims to examine the changes in air quality during different phases of the COVID-19 pandemic, including the lockdown (LD_{1-4}) and unlock period (UL_{1-2}) (post-lockdown) as compared to pre-lockdown (PL_{1-3}) and to establish the relationships of the environmental and demographic variables with COVID-19 cases in the state of Maharashtra, the worst-hit state in India. Atmospheric pollutants such as $PM_{2.5}$, PM_{10}, NOx, and CO were substantially reduced during the lockdown and unlock phases with the greatest reduction in cities having larger traffic volumes. Compared with the immediate pre-lockdown period (PL_3), the averaged $PM_{2.5}$ and PM_{10} reduced by up to 51% and 47% respectively during the lockdown periods, which resulted in 'satisfactory' level of air quality index (AQI) as a result of reduced vehicular traffic and industrial closing. These parameters continued to reduce as much as 80% during the unlock periods due to the additive impact of weather (rainfall and temperature) combined with the lockdown conditions. Kendall's correlation matrix showed a significant negative correlation between temperature and air pollutants ($r = -0.35$ to -057). Conversely, SO_2 and O_3 did not improve, and in some cases, they increased during the lockdown and unlocking. COVID-19 spreading incidences were strongly and positively correlated with temperature ($r < 0.62$) and dew point ($r < 0.73$). Thus, this indicates that the increase in temperature and dew point cannot weaken the transmission of this virus. The number of COVID-19 cases relative to air pollutants was negatively correlated ($r = -0.33$ to -0.74), which may be a mere coincidence as a result of lockdown. However, based on pre-lockdown air quality data and demographic factors, it was found that particulate matter ($PM_{2.5}$ and PM_{10}) and population density are closely linked with higher morbidity and mortality although a more in-depth research is required in this direction to validate this finding. The onset of COVID-19 has allowed us to determine that 'immediate' changes in air quality within densely populated/industrialized areas can improve livelihood based on pollution mitigation. These findings could be used by policymakers to set new benchmarks for air pollution that would improve the quality of life for major sectors of the World's population. COVID-19 has shown us that we can make changes when necessary, and findings may pave the way for future research to inform policy on the tough choices we will have to make between quality of life and survival. Also, our results will enrich the ongoing discussion on the role of environmental factors on the transmission of COVID-19 and will help to take necessary steps for its control.

Keywords COVID-19 pandemic · Air pollutants · Meterological factors · Population density · Maharashtra

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Introduction

The novel coronavirus disease (COVID-19), which is caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), was first reported in the Wuhan city of China on 1st December 2019 (WHO 2020). This virus is extremely infectious and quickly spreads to several other countries. Thus, WHO has officially declared this as a global pandemic on 11 March 2020 (WHO 2020; Cucinotta and Vanelli 2020). As of 9 July 2020, the coronavirus has infected more than 12 million people and over 550,159 deaths have been reported from 184 countries (WHO 2020; Johns Hopkins University 2020). Therefore, it has resulted in a global health crisis and a huge challenge for the world in our time (United Nations Development Programme, 2020). India is also facing similar challenges as this virus is spreading exponentially to all corners of the country with the total number has gone up to 767,296 confirmed cases and 21,129 deaths until 9th July 2020 (COVID19INDIA 2020); thereby, it has created an emergency situation in several states. Maharashtra is one of the worse affected states in India with a fatality rate of 4%, which is significantly higher than the rest of the countries with a confirmed total of 223,724 cases, including 123,192 recoveries and 1700 deaths as of 9th July 2020 (MoHFW 2020). The State and Central Government are taking several actions to manage this critical situation. After a self-quarantine curfew, called as 'Janta Curfew', the Government of India has imposed a complete lockdown from March 25 to April 14, 2020, for 21 days (phase 1) and subsequently this has been extended to phases 2, 3, and 4 to avoid further spread of the virus. This entailed self-isolation, a significant reduction of travel both on the road and air, and a halt to various other outdoor activities, including industrial, commercial, construction, etc. (MHA 2020). As a consequence, this lockdown has led to a very rare positive impact on the natural environment, especially a significant improvement in the air quality in various parts of the world. This could be a blessing in disguise (Muhmmad et al. 2020) as air pollution is one of the major life threats that results in numerous health diseases including cardiovascular and respiratory illness, asthma, bronchitis, chronic obstructive pulmonary disease, stress to lung and heart, and shortened life span (Gorai et al. 2016; Li et al. 2018; Pani et al. 2019, 2020a). The first lockdown impact on air quality has been reported for NO_2 from Wuhan, China (NASA 2020). Thereafter, other studies have reported a drastic reduction of $PM_{2.5}$, PM_{10}, NO_x, and CO during the lockdown period from several cities of China, New York, São Paulo, Barcelona, and others (Xu et al. 2020; Tobías et al. 2020; Dantas et al. 2020; Krecl 2020). In India, this has been studied in some major cities like Delhi, Mumbai, Hyderabad, Kolkata, etc (Jain and Sharma 2020; Bera et al. 2020; Sharma et al. 2020; Mahato et al. 2020). However, these studies examined the early trend only and it is still not clear what has happened after the lockdown is lifted. Also, it has been mentioned that change in air quality due to COVID-19 has been different in

different regions/places and may not follow a similar trend (Masum and Pal 2020). Therefore, it is important to have a local study to evaluate the pattern of changes.

Furthermore, since the beginning of this outbreak, numerous researches have been going on to understand the factor affecting the transmission of SARC-CoV-2, in particular trying to find the link of host immunity, population density, and climate/environmental conditions (Pequeno et al. 2020; Wu et al. 2020a, b; Li et al. 2020). Air pollution is known to cause numerous respiratory diseases and it is the longer the exposure, the higher is the risk theory (Gorai et al. 2016); therefore, there has been considerable interest in understanding whether ambient air pollutants such as $PM_{2.5}$, PM_{10}, NO_x, and CO are associated with the incidence of the COVID-19 (Zoran et al. 2020; Li et al. 2020). Some studies reported that poor air quality is linked with the severity of COVID-19 outcomes (Ogen 2020; Wu et al. 2020b; Zoran et al. 2020; Li et al. 2020). Furthermore, it has been documented that variation in temperature and humidity leads to influenza and other respiratory viruses such as severe acute respiratory syndrome (SARS), etc. (Tan et al. 2005). Considering this logic, several studies aimed to find the role of meteorological parameters like temperature, relative humidity, dew point, wind speed, and rainfall in the spread of COVID-19 (Sahoo et al. 2020, 2021; Pani et al. 2020b; Wu et al. 2020b; Ma et al. 2020). Other factors including demographic factors such as population density, household age profiles, and sex-ratios are also reported to be linked with this pandemic (Cruz et al. 2020; Hamidi et al. 2020; Babbitt et al. 2020). However, the conclusions of these studies are still controversial. Furthermore, this topic is still at an early stage and there is insufficient data at this moment. Moreover, the spread of COVID-19 can vary from one region to another depending upon the local weather and environmental conditions as well as government guidelines, etc. Therefore, more careful and vigorous studies are required for any region considering these factors for an accurate assessment of this epidemic.

Keeping this in view, the present study aims to evaluate the lockdown and unlock impact on air quality and explore the association between environmental conditions (including meteorological parameters and ambient air pollutants), demographic factors, and COVID-19 incidence/mortality in the state of Maharashtra, India.

Materials and methods

Study area

Maharashtra is the third most urbanized and highly developed state in India, located in the western part of the country (Fig. 1). The state has 36 districts and it is the most industrialised state in India. The total population of this state is
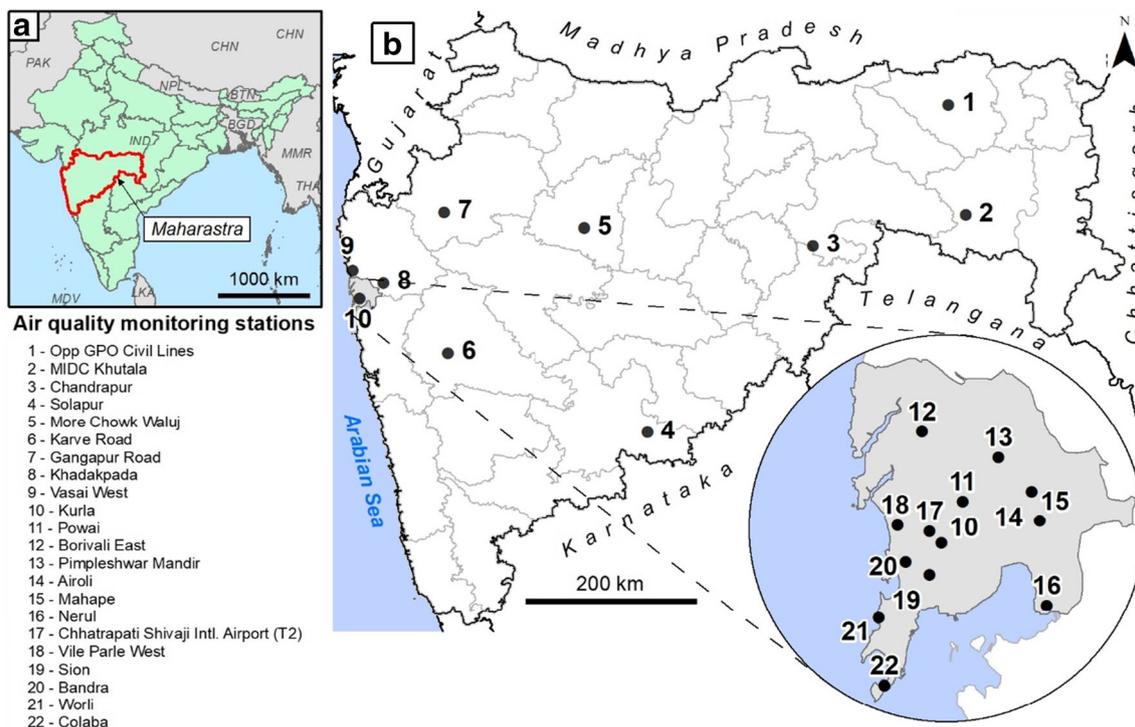
Fig. 1 Map showing the outline of the study area and the location of 22 air quality monitoring stations in Maharashtra, India

112 million with approx. 50% population urban and 46% less than 24 years of age (Maji et al. 2016). Mumbai is the capital of this state and is the highest populated city (with a population of 13 million) in India. The average rainfall ranges between 650 and 750 mm. The region has a tropical wet and dry climate. The rainy season lasts from June to September followed by winter from November to February during which the minimum temperature ranges between 9 and 10 °C. The summer ranges from March to June in which the temperature shoots up to 45 °C and humidity being approximately 70 to 85%.

Data collection

The daily average concentrations (all stations) of air pollutants such as $PM_{2.5}$, PM_{10}, CO, NO, NO_x, NO_2, SO_2, ozone, toluene, benzene, and the basic meteorological parameters such as ambient temperature (AT), rainfall (RF), and wind speed (WS) have been considered to evaluate the deviation of air quality in pre-, during, and post-lockdown period from 1 January to 3 July 2020. Dew point temperature (DP) was calculated using the following equation: DP = T – (100–RH)/5, where 'T' is atmosperic temperature and 'RH' is relative humidity (Lawrence 2005). A total of 22 monitoring stations which are comprised of several major cities such as Mumbai, Pune, Thane, Navi Mumbai, Nagpur, Solapur, Chandrapur, Kalyan, and Aurangabad are considered to cover the entire state of Maharashtra (Fig. 1). The data related to these parameters were obtained from the Central Pollution Control Board (CPCB, India) online portal (https://app.cpcbccr.

com/ccr/#/caaqm-dashboard-all/caaqm-landing). The daily averaged air quality index (AQI) data were retrieved from the World's Air Pollution online platform (https://waqi.info/). The AQI was calculated following the method (Eq. 1) prescribed by CPCB (CPCB 2014; Sharma et al. 2020). This index uses the concentration of PM_{10}, $PM_{2.5}$, SO_2, NO_2, O_3, NH_3, and CO (up to 24-hourly averaging period), of which a minimum of three pollutants must be considered with at least one of being $PM_{2.5}$ or PM_{10} (CPCB 2014).

$$AQI_i = \frac{IN_{HI} - IN_{LO}}{B_{HI} - B_{LO}} \ x \ (C_i - B_{LO}) + IN_{LO} \qquad (1)$$

where, B_{HI} and B_{LO} as breakpoint concentrations greater and smaller to C_i; IN_{HI} C_i as the concentration of pollutant i; IN_{HI} and IN_{LO} are corresponding AQI values. The AQI is followed as good (0–50), satisfactory (51–100), moderate (101–200), poor (201–300), very poor ($30_{1-4}00$), and severe (401–500) (CPCB 2014; Sharma et al. 2020).

Daily new cases of COVID-19 data (total infection, recovery, and death cases) were collected from the government of Maharashtra COVID-19 portal and from the website (i.e. https://api.covid19india.org/csv/) between 14 March 2020 and 3 July 2020. Other parameters related to this study are taken from the government's official sources. The data representing as pre (PL_1: 1 January to 31 January; PL_2: 1 February to 29 February; PL_3: 1 March to 24 March), during (LD_1: 25 March to 14 April; LD_2: 15 April to 3 May; LD_3: 4 May to 17 May; LD_4: 18 May to 31 May) and unlock periods (UL_1: 1 June to 30 June; UL2: > 1 July).

Statistical and spatial analysis

The Kendall rank correlation, a non-parametric test, was used to estimate the ordinal association between variables such as air pollutants, weather parameters, and COVID-19 incidences. The p values of < 0.01 are considered statistically significant. Kendall correlation is preferred over Spearman's correlation as the former is more robust and efficient because of a smaller gross error sensitivity (GES) (more robust) and a smaller asymptotic variance (AV) (more efficient). Kendall's tau also produces smaller and more realistic values than Spearman's rho. Thus, in our study, the Kendall's tau correlation matrix was considered (Howell 2012). Normality of the dataset was checked by using a combination of EDA plot and Shapiro-Wilk's (S-W) test. The Kruskal-Wallis test, a non-parametric version of the ANOVA, was performed on air quality and meteorological data. The null hypothesis for this test is that the mean concentrations of each variable between different periods are not significantly different at a level of significance $p > 0.05$. Furthermore based on city-wise data, the relationship of pre-lockdown air quality data (the maximum average value was taken between PL_{1-3}) and the demographic variables such as population size, density, and literacy with COVID-19 data was established using correlation analysis based on symmetric pivot coordinates, which solves the issue of data collinearity. All statistical treatments were performed by using R statistical software version 3.5 (R Core Team 2018) and MS-Excel 2016. Spatial distribution analysis of air pollutants was carried out using Geographic Information System (GIS) environment (ArcGIS 10.6) under the World Geodetic System 1984 (WGS84) datum.

Results

The daily variation averaged over all stations of various air pollutants ($PM_{2.5}$, PM_{10}, NO_x, NO, NO_2, CO, SO_2, ozone, toluene, benzene) and air quality index (AQI) during the different time periods, including pre-lockdown (PL_{1-3}), lockdown (LD_{1-4}), and unlock (UL_{1-2}) from 1st January to 3rd July, are shown in Figs. 2 and 3. The number of incidents of each pollutant exceeding the National Ambient Air Quality Standards (NAAQS) defined by (CPCB) and percentage change in average pollutant levels during the different periods of LDs and ULs with respect to the immediate pre-lockdown (PL_3) are given in Table 1; the station-wise percentage changes are given in Table 1SM. It has been observed that in most of the pollutants like $PM_{2.5}$, PM_{10}, NO_x, NO_2, CO, benzene, AQI show a sharp declining trend with up and down spikes (Fig. 2), and a significant reduction during the lockdown periods. For pollutants like $PM_{2.5}$ and PM_{10} and AQI, this reduction was even greater during the ULs, but for some gaseous pollutants like CO, NO, and NO_x, this trend is slightly increased

in the ULs (Fig. 2). The Kruskal-Wallis test (Table 2) shows that most of the air quality parameters had p values < 0.05 pollutants, which indicates that these pollutants were significantly varied among the different phases of lockdown and unlock. When compared with the NAAQS limits, average concentrations of PM_{10} in PL_{1-3} phases were mostly exceeding its permissible limit, i.e. 100 μg/m^3 (Table 1); however, these levels were drastically reduced well below its permissible limit in both LDs and ULs. The PM_{10} level (averaged of all stations) was reduced up to 51% in the LDs and further declined up to 80% in the ULs compared with PL_3. Similarly, $PM_{2.5}$ was dropped significantly up to 46% in LDs and up to 78% in ULs, and in both cases, it was noticed that the reduction in $PM_{2.5}$ levels was well below it permissible limits, i.e. 60 μg/m^3. Compared with the PLs, NO_x (which consists of NO and NO_2) is significantly declined up to 62% in LDs and a little lower up to 50% in the ULs. Similarly, NO was dropped significantly up to 63% in LDs but this trend was comparatively lower in ULs (up to 44%). Moreover, the NO_2 levels were lesser than the permissible limit (80 μg/m^3) even before the COVID-19 lockdown. The average concentration of CO was also significantly reduced in the LD phases compared with PDs; the lowest was in LD_4, but the level was slightly increased in ULs in a similar pattern like NO_x. The CO concentration dropped up to 54% and 35%, respectively, in the LD and ULs. Moreover, the CO levels never exceeded the permissible limit, i.e. 2.0 mg/m^3 in the entire studied period. Among the gaseous pollutants, the reduction of ozone was much lower in LDs (up to 18%), but it has significantly dropped in the ULs (up to 66%), although irrespective of pre-lockdown and lockdown, ozone was mostly found to be within the standard limit (100 μg/m^3). Similarly, the reduction of SO_2 was lower in the LDs and ULs and was not prominent compared with other pollutants, but it was well below the permissible limit in all periods. Among organic pollutants, benzene was found to be exceeding the standard limit, i.e. 5 μg/m^3 as per CPCB. It was also drastically reduced in the LDs as well as in the ULs in a similar way like toluene, benzene, and oxylene. AQI was an overall assessment of air quality based on the criteria pollutants. During the PLs, the average AQI was mostly between 100 and 200 with the category of moderate quality; however, this level was significantly dropped to below 100 during the lockdown and it has been reduced further to below 50 during the unlock phases.

The spatio-temporal variation of selective parameters in immediate pre-lockdown (PL_3), lockdown ($LD_{1,4}$), and unlock (UL_2) periods is shown in Fig. 4 (other parameters can be found in Fig. 1SM). Also, the station-wise variations are given in Table 1SM to quantify the impact of lockdown over individual stations/cities. It can be noticed that most of the air pollutants were widely varied over the study area with more pollution levels in the western part than other regions. During the immediate pre-lockdown (PL_3), the concentrations of
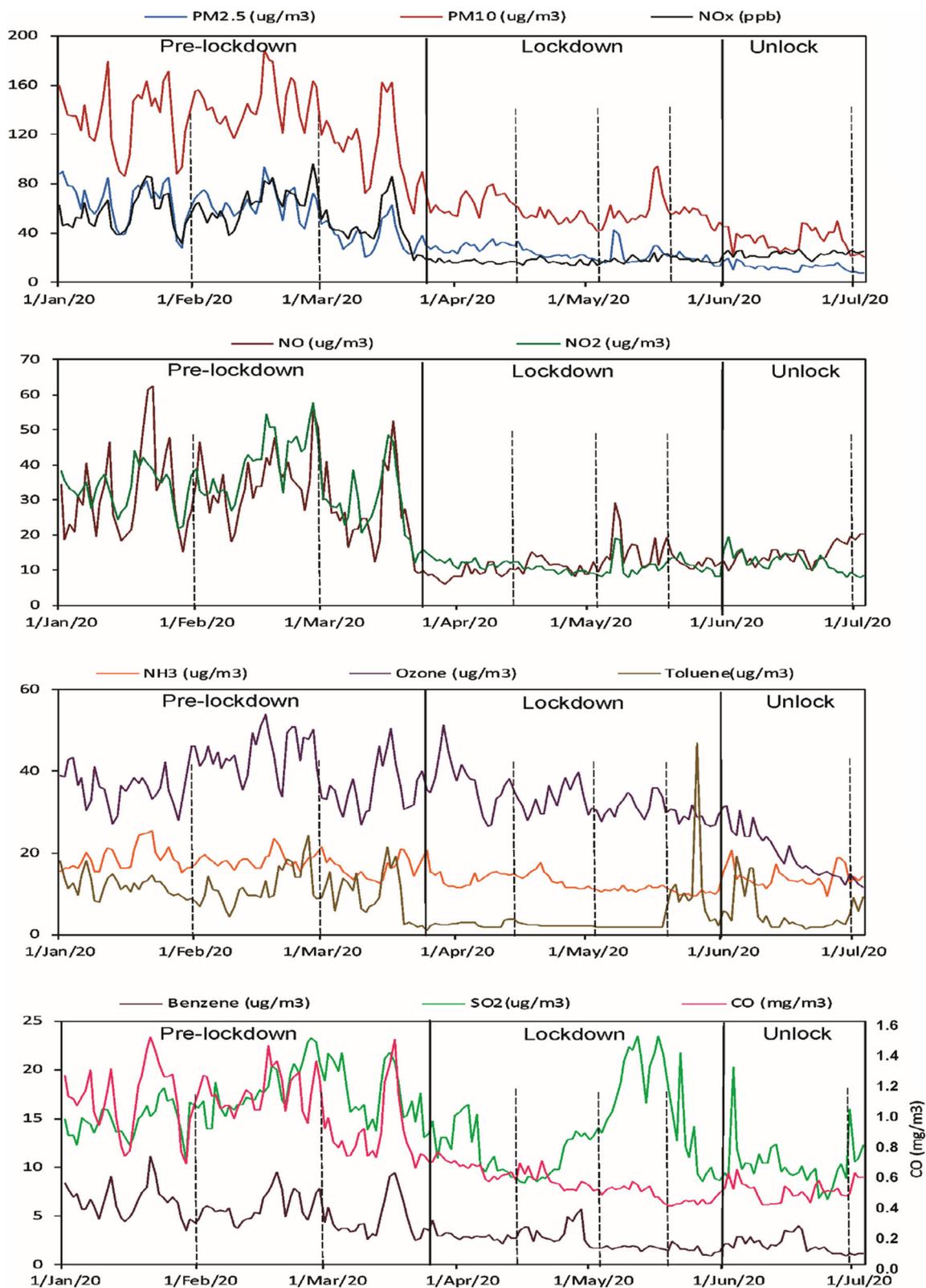
Fig. 2 Temporal variation of daily average level of $PM_{2.5}$, PM_{10}, NO_x, NO, NO_2, NH_3, CO, SO_2, ozone, toluene, and benzene from 1 Jan to 3 Jul 2020 in Maharashtra
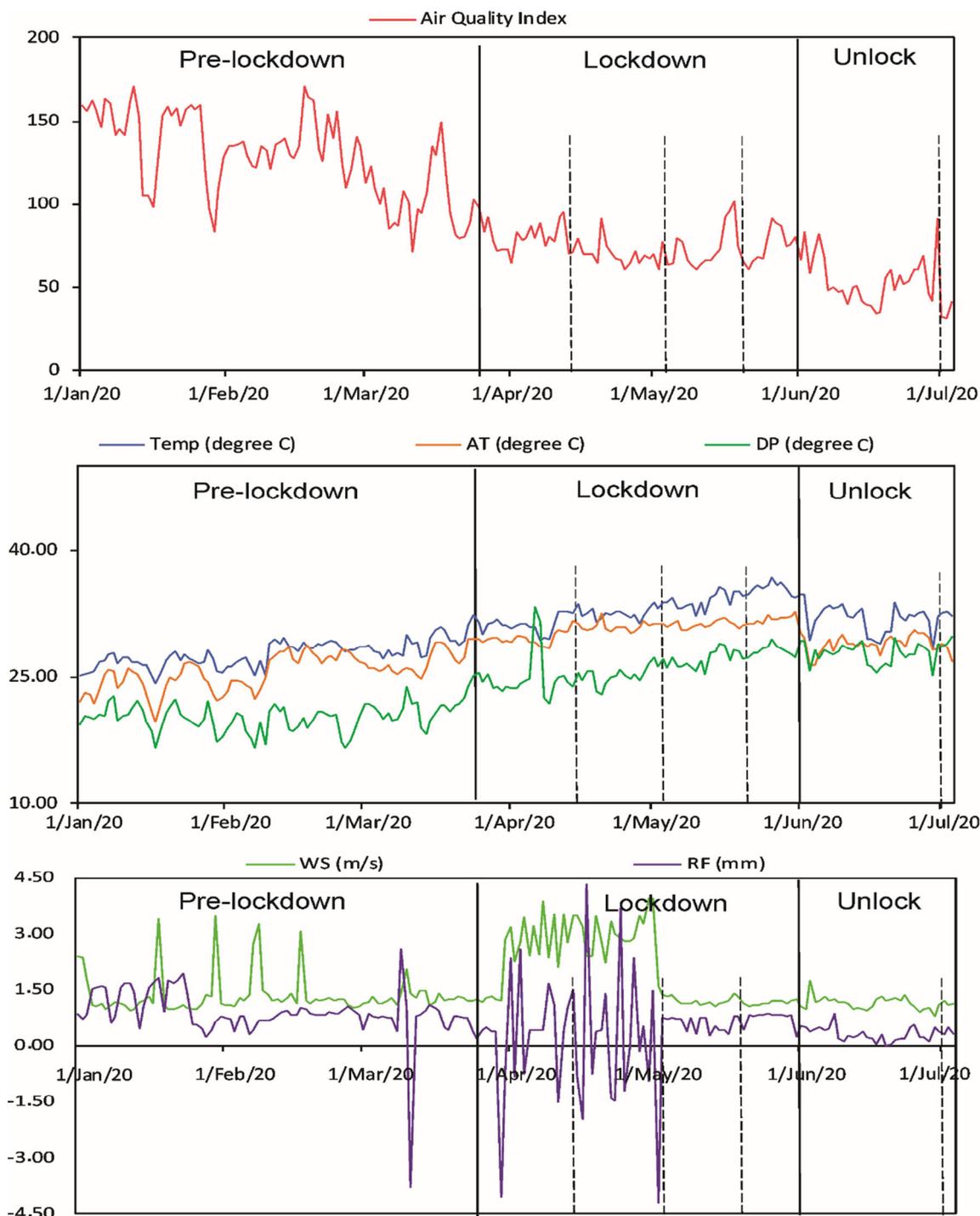
Fig. 3 Temporal variation of daily average level of Air Quality Index (AQI), Ambient Temperature (AT), Temperature (Temp), dew point (DP), windspeed (WS), and rainfall (RF) in Maharashtra from 1st Jan to 3rd Jul 2020

$PM_{2.5}$ and PM_{10} were higher in Mumbai (Airport (T2), Powai, Sion, Vile Parle, Kurla), Navi Mumbai (Mahape, Nerul), Kalyan, and Solapur, similar with AQI. All these stations witnessed a significant reduction of these pollutants during the lockdown and unlock phases. Similarly, NO_2 was reduced in most of the stations during LDs and ULs, unlike CO, NO_x, benzene, which show an increasing trend in some stations.

SO_2 shows a little variation between stations during PLs, LDs, and ULs, with the highest values recorded in the Kalyan region. Ozone was also less varied during the lockdown, and particularly shows an increasing pattern in some stations during LD1, but in stations like More Chowk Waluj in Aurangabad, it continued to increase in all the phases of LD and UL.

Table 1 (a) Number of incidents of daily average pollutants exceeding the NAAQS limit during the pre-lockdown (PL_{1-3}), lockdown (LD_{1-4}) and unlock (UL_{1-2}) periods in Maharashtra from 1st January to 3rd July. (b) Percentage change in average pollutants and meteorological parameters during the LD_{1-4} and UL_{1-2} phases with respect to the immediate pre-lockdown period (PL_3)

(a) No. of incidents exceeding the NAAQS limit

Parameters	PL_1	PL_2	PL_3	LD_1	LD_2	LD_3	LD_4	UL_1	UL_2
PM_{10}	26	29	15	0	0	0	0	0	0
$PM_{2.5}$	20	19	1	0	0	0	0	0	0
CO	0	0	0	0	0	0	0	0	0
NH_3	0	0	0	0	0	0	0	0	0
NO	0	0	0	0	0	0	0	0	0
NO_2	0	0	0	0	0	0	0	0	0
NO_x	0	0	0	0	0	0	0	0	0
Ozone	0	0	0	0	0	0	0	0	0
SO_2	0	0	8	0	2	0	0	0	0
Benzene	23	21	ND	ND	ND	ND	ND	ND	ND
O-Xylene	ND	ND	ND	ND	ND	ND	ND	ND	ND
Toluene	ND	ND	ND	ND	ND	ND	ND	ND	ND
WS	ND	ND	ND	ND	ND	ND	ND	ND	ND
AT	ND	ND	ND	ND	ND	ND	ND	ND	ND
Temp	ND	ND	ND	ND	ND	ND	ND	ND	ND
RH	ND	ND	ND	ND	ND	ND	ND	ND	ND

(b) % change w.r.t immediate pre-lockdown (PL_3)

Parameters	LD_1	LD_2	LD_3	LD_4	UL_1	UL_2
PM_{10}	− 40.3	− 50.8	− 45.9	− 48.3	− 67.2	− 80.2
$PM_{2.5}$	− 21.6	− 40.5	− 39.5	− 46.5	− 64.1	− 78.3
CO	− 28.2	− 38.6	− 46.7	− 54.7	− 45.3	− 34.7
NH_3	− 18.6	− 23.0	− 36.8	− 37.0	− 15.6	− 23.3
NO	− 63.2	− 55.4	− 29.9	− 47.6	− 44.4	− 17.5
NO_2	− 56.4	− 64.6	− 59.3	− 59.1	− 53.8	− 68.4
NO_x	− 61.0	− 62.4	− 53.0	− 57.9	− 49.5	− 41.0
Ozone	7.4	− 5.0	− 17.3	− 18.8	− 41.4	− 63.4
SO_2	− 19.9	− 31.9	9.3	− 20.9	− 42.6	− 22.5
Benzene	− 36.7	− 33.6	− 62.0	− 59.4	− 58.3	− 78.2
O-Xylene	− 68.1	− 69.8	− 65.6	− 80.6	− 82.7	− 79.2
Toluene	− 75.6	− 77.8	− 81.8	− 5.9	− 50.3	− 30.0
WS	120.7	122.3	− 8.1	− 2.3	− 13.0	− 9.5
AT	9.6	15.6	15.9	17.4	7.5	3.7
Temp	6.9	12.1	16.3	21.8	12.0	11.5
RH	78.1	4.8	6.2	7.1	33.5	40.3

ND no data; *AT*: atmospheric temperature; *RH*: relative humidity; *Temp*: temperature; *WS*: wind speed

The daily averaged variation over all stations of meteorological parameters is shown in Fig. 3. The temperature shows a moderately increasing trend from 1 January to 3 July, similar with DP. Overall, WS and RF show a slight variation in the study period with abnormal fluctuations in April and May. The Kruskal-Wallis test (Table 2) shows a p value < 0.05 for most of the meterological parameters, although rainfall had a relatively low Z score as compared with others.

Daily COVID-19 incidences including confirmed, recovered and death cases are presented in Fig. 5. This shows a speedy growth of the COVID-19 cases for Maharashtra starting from 14 confirmed cases on March 14, 2020, which rose to 125 until the March 26 (PL), 2916 until 15 April and then spiked rapidly to 67,655 cumulative cases until 31 May (the end of LD_4) and 192,990 cumulative cases until 3 July 2020 (beginning of UL_1). The highest and lowest daily COVID-19 incidences in Maharashtra were 6364 cases on 1st July and 3 cases on 17 March, respectively, as of 3 July. At the same pace, the number of recoveries and death cases are also increasing. Until 1 July, the total number of death cases were 6014, and the highest (1409 cases) was on 15 June.

Table 3 presents the result of Kendall's tau correlation analysis of air pollutants and meteorological variables and daily COVID-19 incidences. This has been calculated based on the data from 1 Jan 2020 to 3 July 2020. The Kendall's correlation matrix showed that most of the ambient air pollutants particularly $PM_{2.5}$, PM_{10}, CO, and NO_x were moderately negatively correlated with atmospheric temperature ($r = − 0.32$ to 0.57). Similarly, air pollutants are weakly negatively correlated with wind speed ($r = − 0.02$ to − 0.29), and weakly positively correlated with rainfall ($r = 0.2$ to 0.36). Among the air pollutants, $PM_{2.5}$ and PM_{10} show a strong positive correlation with each other ($r = 0.82$) and they are mostly moderately positively correlated with other pollutants. Furthermore, we studied the correlation between environmental parameters and COVID-19 incidences (Table 2 and Fig. 5), which is calculated from 1 January 2020 to 3 July 2020 (Table 3). This shows that temperature ($r = 0.58$ to 0.62) is predominantly positively correlated with COVID-19 incidence and death cases. Dew point also shows a strong positive correlation with COVID-19 incidences ($r = 0.71$ to 0.73). Most of the air pollutants are significantly negatively correlated ($r < − 0.67$) with COVID-19 (Table 3). Rainfall and wind speed are weekly and negatively correlated with COVID-19 cases (Table 3). The relationship between daily COVID-19 confirmed cases and meteorological parameters is shown in Fig. 6. Furthermore, heat-plot (Fig. 7) shows the correlation between demographic factors, air pollutants (this is based on the maximum average concentration during the pre-lockdown phases—PL_{1-3}) and COVID-19 incidence. This indicates that COVID-19 cases and deaths are more closely related to population density and $PM_{2.5}$ and PM_{10}.

Discussion

Impact of lockdown and unlock phases and the meteorological factors on air quality

A sharp decline in most of the major air pollutants like $PM_{2.5}$, PM_{10}, NO_2, and CO along with AQI in most of the cities during lockdown (Fig. 2, 3) clearly illustrates a rare benefit and a blessing of forced lockdown that shut down most of the anthropogenic activities such as industries, heavy traffic, road, and infrastructure construction activities, which are substantial contributors to both fractions of particulate matter and other air pollutants (MPCB 2019; Masum and Pal 2020). Furthermore, the greater reduction of these pollutants in major stations like Khadakpada (Kalyan), Kurla (Mumbai), Nerul (Navi Mumbai), Chhatrapati Shivaji Int. Airport (Mumbai) (Table 1SM), which displayed trends of higher PMs level among other regions during pre-lockdown, further evidenced that larger cities have a higher improvement in air quality and vehicular emission along with industrial establishments and a high level of urbanization are the major contributor of PMs. Similarly, a significant fall of NO_2 levels in lockdown phases and a maximum decline in densely populated and busy traffic regions, like Chhatrapati Shivaji Intl. Airport (Mumbai), Mahape (Navi Mumbai), Sion (Mumbai), and Vasai West (Mumbai), indicate motor vehicle exhaust and industrial activities are the major sources of NO_x. SO_2 was the least impacted pollutant, which did not show a clear reduction trend in the LDs. In fact, this is increased in some stations during the lockdown as well as unlock periods. This is possibly due to some small/medium to heavy industries including the coal-based thermal power plants which were likely to be operating during these periods. Maximum SO_2 content in the Kalyan region is due to the presence of industrial setups and having numerous manufacturing units (MPCB 2018, 2019). The major toxic organic pollutants such as benzene, toluene, xylene, and ethyl benzene were also significantly reduced in both lockdown and unlock phases. Benzene is one of the ingredients of petroleum products and it is mainly released to the atmosphere via petrol and diesel exhausts and petrol

evaporation from vehicles as well as from industrial activities such as refinery and petrochemicals, etc. (CPCB 2012). Toluene and xylene are also present in the above-mentioned source along with benzene (CPCB 2012). Thus, shutting down of the transport (including road, rail, aviation) and industrial sectors is the major reason for the sharp decline in these pollutants during the lockdown phases. In India, a significant reduction of criteria air pollutants and a drastic improvement in AQI was also witnessed from major cities like Delhi, Mumbai, Bangalore, Kolkata, Chennai, Punjab, and Chandigarh (Jain and Sharma 2020; Sharma et al. 2020; Mahato et al. 2020; CPCB 2020; Sahoo et al. 2021). Particulate matters have significantly reduced all over India with a maximum decline in northern India, while the average decrease for PM_{10}, $PM_{2.5}$, NO_2, and CO across India during lockdown was 40.5%, 35%, 27.9%, and 13.9%, respectively (Navinya et al. 2020). In another study, Ghosh et al. (2020) reported a significant drop of PM_{10} (64.6%), $PM_{2.5}$ (60.9%), NO_2 (76.8%), and VOC (69%) from different monitoring stations located across Kolkata. Several other studies worldwide from major cities of Brazil, China, Spain, Italy, Kazakhstan, Germany, France, etc. also reported a sharp decline in air pollutants like $PM_{2.5}$, PM_{10}, CO, NO_2, and SO_2 during COVID-19 strict quarantine periods (Xu et al. 2020; Tobías et al. 2020; Dantas et al. 2020; Otmani et al. 2020; Kerimray et al. 2020). ESA (2020) reported almost 20–30% reduction of NO_2 in France, Spain, Italy, and Germany during the lockdown phase. Reduction of PMs was over 40% reported in urban areas in China, while it was dropped by 19–40% in the USA (Xu et al. 2020; Tobías et al. 2020; Berman and Ebisu 2020). The strong positive correlation between $PM_{2.5}$, PM_{10}, NO_2, and CO suggests a common source possibly from industrial sources and automobiles combustion which are common to both fractions of PMs, NO_x, and CO (Table 3). The poor relationship between SO_2 and NO_2 could be due to different sources particularly from diesel engines of buses and lorries and industrial emission. Ozone is a secondary pollutant, which is produced chemically by the photolysis of nitrogen compounds (NO_x) and volatile organic compounds (VOCs) under sunlight (Fang et al. 2020). Despite the

Table 2 Kruskal-Wallis test results of the chemical parameters among grouping variables (lockdown and unlock periods)

	Statistic value														
	$PM_{2.5}$ µg/m³	PM_{10}	NO	NO_2	NH_3	Ozone	Benzene	Toluene	SO_2	CO mg/m³	AQI	WS m/s	AT C	RH %	RF mm
H statistics	95.73	101.3	68.50	74.23	68.07	79.17	76.45	55.54	67.08	101	79.34	75	99.5	70.6	29.79
Asymp. Sig.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Grouping variables: lockdown (LD_1, LD_2, LD_3, LD_4) and unlock (UL_1, UL_2) periods; values < 0.05 for the asymp. sig. (2-tailed) is significantly different between groups
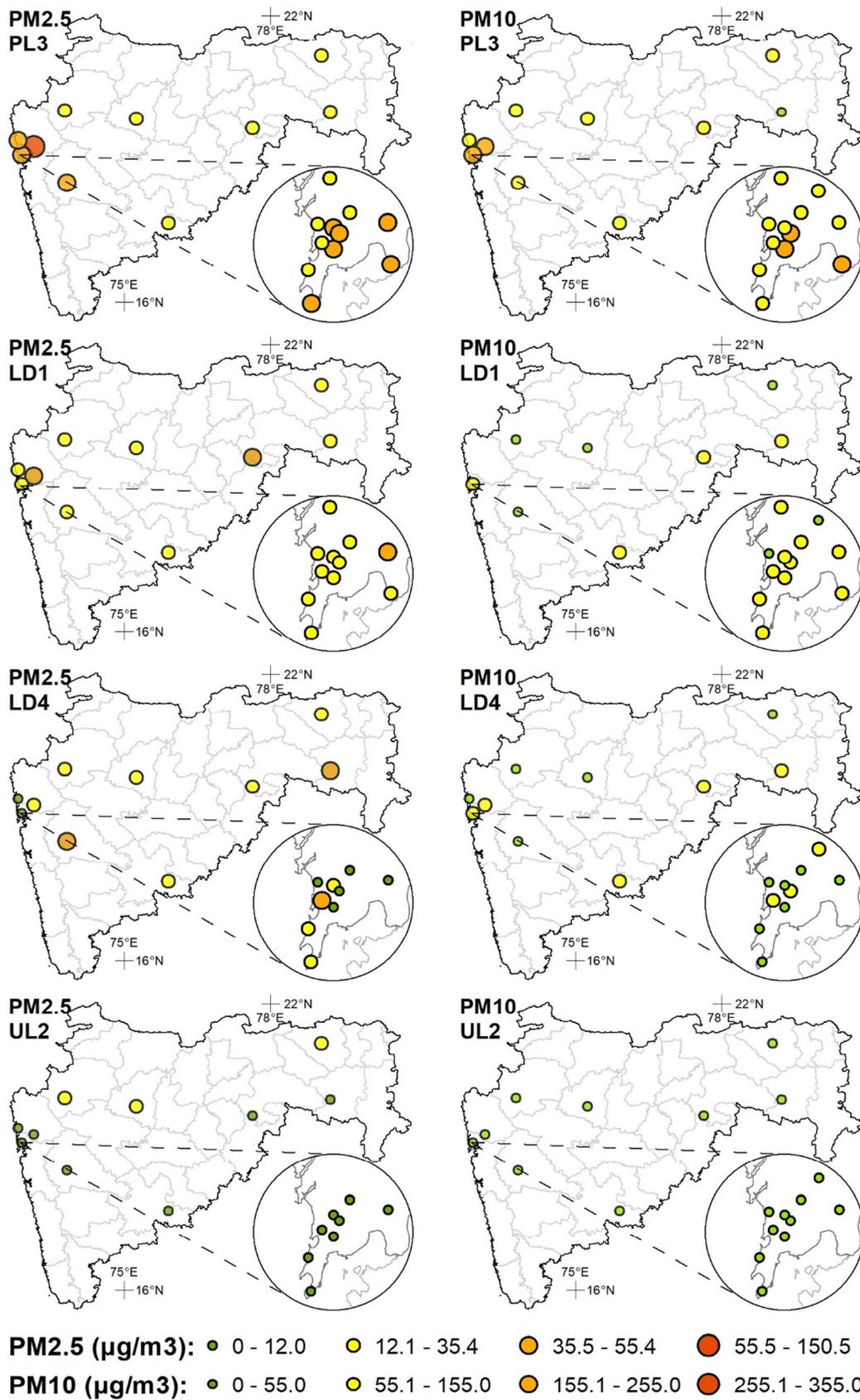
Fig. 4 Spatial distribution of PM$_{2.5}$ and PM$_{10}$, NO$_2$, NO$_x$, CO, and SO$_2$ in pre-lockdown (PL$_3$), lockdown (LD$_{1-4}$) and unlock (UL$_{1-2}$) periods in Maharashtra.
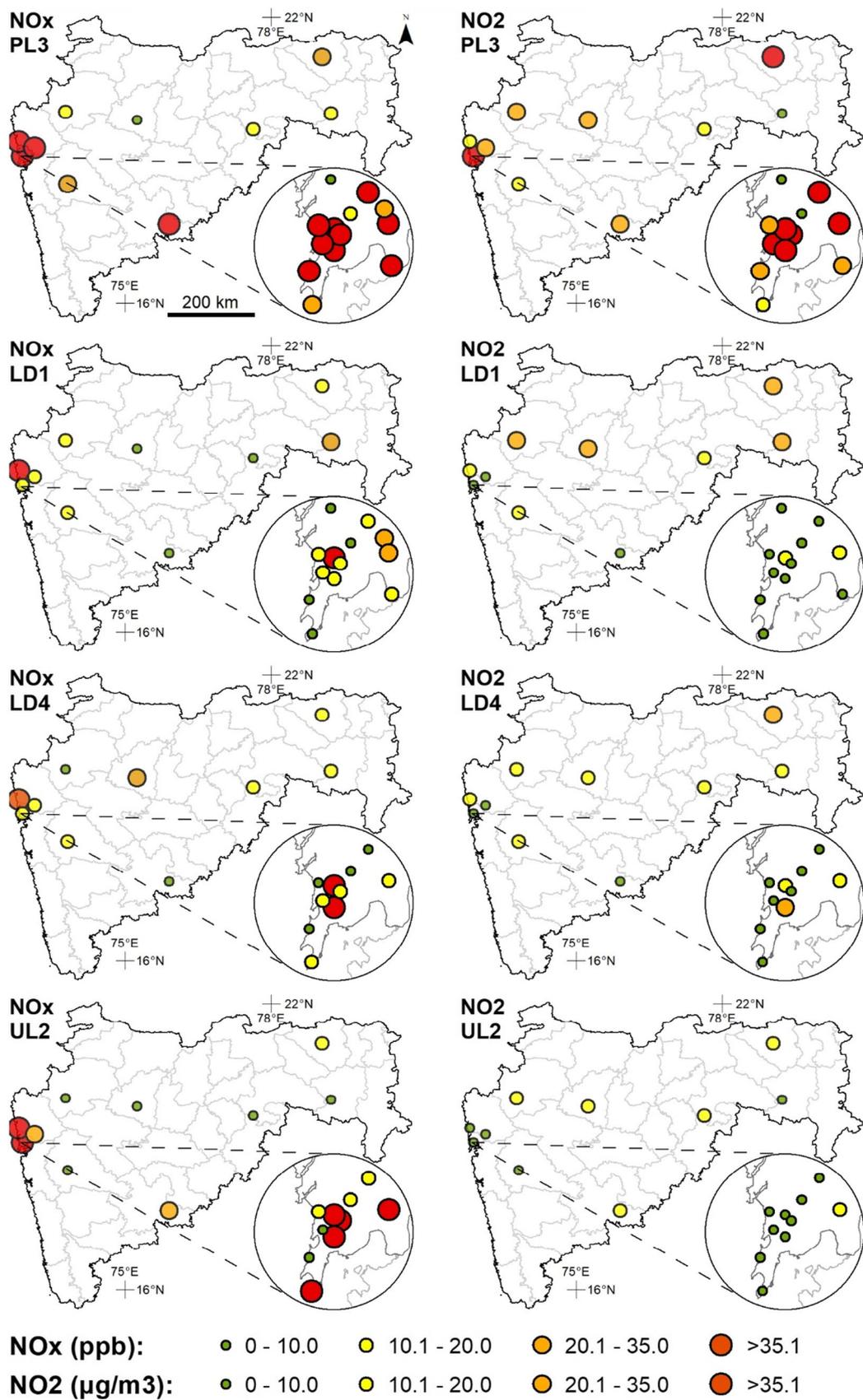
Fig. 4 continued.

reduction in traffic pollution during the lockdown phases, the increasing level of O_3 in the lower atmosphere mainly in lockdown phase 1 and its weak correlation with NO_2 is possibly due to low consumption of O_3 as a result of less emission of NO_2, which is due to no industrial activities and vehicles were off the road during the lockdown (Sharma et al. 2020; Tobías et al. 2020). A similar findings of an increase of O_3 in the lower atmosphere during the COVID-19 lockdown days also reported in other studies (Sahoo et al. 2021; Bera et al. 2020; Shi and Brasseur 2020). As the lockdown eases and the vehicles returned on roads road in the unlock phases, the pollution started to increase. This is evident from the increasing concentrations of CO, NO_2, and NO_x from the cleanest lockdown phase. However, PM_{10} and $PM_{2.5}$ have been dropping continuously even during the unlock period, which is due to the reduction of construction and industrial activities as well as intermittent rainfall. The rain helped wash away the particulate matters, which further helped to decrease AQI well below 50 'good' categories during the unlock periods. Overall, Maharasthra has witnessed nearly a 45-70% decline in air pollution during the lockdown and unlock phases. The contribution of $PM_{2.5}$ and PM_{10} was maximum to the AQI variability, thus these parameters are crucial to maintaining the air quality level. Thus, in the coming years curbing vehicular and industrial emissions and temporary lockdown mechanism could be used as an essential measure to decrease the pollution (Bera et al. 2020). Thus, the lesson learnt in this lockdown due to COVID-19 could be thought-provoking for policymakers to be used as a marker or baseline level to develop strategies for better air quality or manage air pollutants in urban cities that are often overlooked directly or indirectly (Masum and Pal 2020).

Meteorological impacts such as a change in summer temperature, relative humidity, rainfall, and wind speed have an important role in controlling the air pollutants (Sharma et al. 2020; Navinya et al. 2020). The lower temperature in pre-lockdown from January to March 2020 could lower mixing height of air and cold conditions trap air pollutants and may be one of the causes of increasing concentrations of all the criteria pollutants during winters, while higher temperature during the lockdown phase 4 and unlock phases may have contributed in the dispersion of pollutants. This is clearly evident in the significant negative correlation between temperature and most of the air pollutants (Table 3). These findings indicate that the influence of temperature on gaseous pollutants is much more effective in summer than other seasons due to the higher temperature range. This is corroborated with the previous studies (Sharma et al. 2020), while relatively small changes in humidity and wind speed during pre-lockdown, and lockdown indicate little impact on air quality. Moreover, although rainfall shows a weak relationship with most of the air pollutants, scattered rainfall during the lockdown and unlock periods could help washing away particulate pollutants and result in

further improvement in air quality. Ozone is also greatly influenced by weather conditions, in particular O_3 concentration increases with an increase of ambient temperature and solar radiation (Ghosh et al. 2020), in this study we have not observed any significant relationship. Overall, it can be observed that the changes in the meteorological conditions play a role in influencing air quality; but, these changes are less pronounced to induce such drastic reductions of air pollution well below the permissible limit, and thus the sharp decline in pollution levels during lockdown is predominantly influenced by the shutting down of anthropogenic activities during the lockdown (Navinya et al. 2020; Dutheil et al. 2020). However, during the unlock period an additional factor such as intermittent rainfall could lead to the removal of airborne particulate matters, as a result the AQI was further improved.

Correlation between weather conditions and COVID-19 infections

Meteorological parameters such as temperature and relative humidity are reported to be important factors in influencing the transmission of respiratory-borne infectious diseases such as SARS and influenza (Tan et al. 2005; Chan et al. 2011; Vandini et al. 2013; Ma et al. 2020; Davis et al. 2016). These viruses are often more active when the temperatures drop in cold weather and reduce their activity when temperature increases considering the fact that higher temperature damages the lipid layer of the virus (Chan et al. 2011). Similarly, it has been reported that higher RH will attenuate viral activity, and when the humidity is lower, the infected aerosol particles can survive for longer in the air, thereby greater chances of infecting other people (Ma et al. 2020; Ward et al. 2020; Avhad et al. 2020). However, the use of daily (24 hr) average RH is problematic for outdoor, as the daily averaged RH as an independent variable for an analysis of virus spread (Davis et al. 2016). In such scenario, David et al. (2016) suegested to consider dew point (DP) instead of RH. Dew point is the temperature at which air must be cooled to become saturated without changing the pressure and is highly associated with the human comfort. Higher the DP, more discomfort outside because the air's humidity slows the evaporation of perspiration from human body, which prevents the nature's way of cooling (Pani et al. 2020b). In our study, average DP values varies from 18.23 to 33.25 ^oC. This level is quite uncomfortable and it indicates heat stress issues for human outdoor. However, despite being this heat stress issues, the positive correlation between daily COVID-19 cases and DP (Table 3; Fig. 6) indicates that increase of dew point can not weaken the tranmission of this vírus. Furtheremore, it has been expected that COVID-19 cases will slow down in summer when the weather becomes too hot and warmer and will rise in winter. In the line of this evidence, some studies reported that temperature is as an environmental driver of the COVID-19 outbreak

Fig. 5 Daily confirmed, recovered and dealth cases of COVID-19 in Maharashtra from 14 Mar 2020 to 3 July 2020
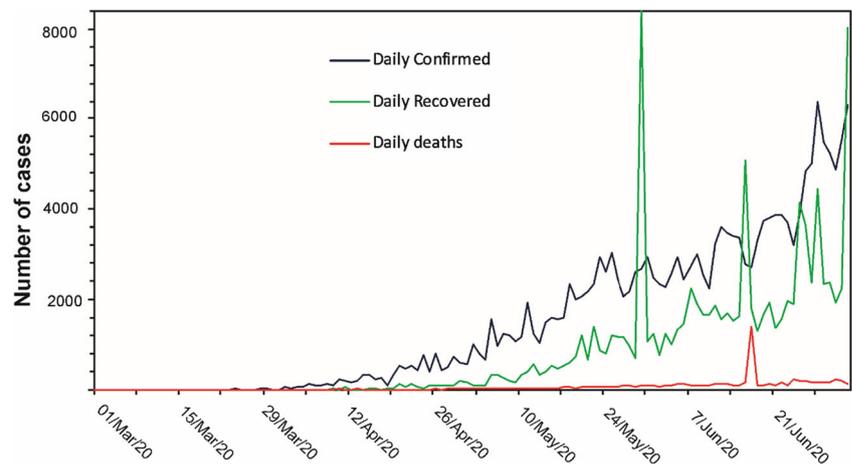
(Shi et al. 2020; Wang et al. 2020; Sajadi et al. 2020; Wu et al. 2020b; Ma et al. 2020). These studies reported that the temperature is negatively related to the daily new cases of COVID-19. Qi et al. (2020) also find that every 1 °C rise of daily average temperature can reduce 36 to 57% daily COVID-19 new cases. Gupta et al. (2020a) also reported that the majority of the COVID-19 cases were found in lower range of temperature 4 to 11 °C. This is very similar with Wu et al. (2020b) who find that 1 °C rise of temperature can reduce 3.08% and 1.19% daily COVID-19 and daily new deaths, respectively, while a 1% increase in relative humidity can decrease 0.85% and 0.51% daily new cases and daily new deaths, respectively. In another study Holtmann et al. (2020) also reported that a rapid spread of COVID-19 is linked with lower ambient temperature. However, our results didn't support this evidence as we observed the COVID-19 pandemic is significantly positively correlated with temperatue (Table 3). A similar positive association with temperature and humidity was reported in other studies in Singapore (Pani et al. 2020b), Punjab, India (Sahoo et al. 2021), Jakarta, Indonesia (Tosepu et al. 2020), and Oslo, Norway (Menebo 2020). In fact, this virus even comfortably survived at high temperatures as recently this pandemic is sharply rising in summer climate in India and in other tropical and sub-tropical countries like Pakistan, Singapore, Brazil. Also, in our study, during the unlock period when the COVID-19 cases were sharply rising, the relationship with temperature was very week (Fig. 6). Thus, our results demonstate that higher temperatures do not decrease the transmission of the COVID-19 significantly. Xie and Zhu (2020) in a study from 122 cities in China also revealed that no evidence of supporting that COVID-19 infections might decline when the weather becomes warmer. Brassey et al. (2020) also stated that weather alone will not be effective to slow the transmission of COVID-19 cases. Other studies also reported that no evidence for COVID-19 transmission with temperature (Gupta et al. 2020b; Sahoo et al. 2020; Yao et al. 2020; Jamil et al. 2020). Furthermore, although

COVID-19 cases are weakly correlated with wind speed, the higher cases at lower WS (Fig. 6) indicate the unventilated air may contribute to the transmission. Previous studies also indicated that windy weather could also help predict the growth of the pandemic (Coşkun et al. 2020; Thomas 2020). In addition, the region receives low precipitation (less than 400 mm) could be one of the reasons to be more vulnerable to the virus (Thomas 2020), but in this study, we have not found any significant relationship with rainfall (Table 3, Fig. 6).

## Relationship between demographic factors, air pollutions, and COVID-19 incidences

In spite of the weather, population density is one of the major factors that may facilitate the faster spread of COVID-19 cases as this virus spreads through close proximity between individuals (Babbitt et al. 2020; Dalziel et al. 2018). Figure 7 shows COVID-19 daily new cases are strongly positively correlated with population size and population density. In Maharashtra, the cities having higher population density are Mumbai (20980) followed by Thane (956), Pune (603), Nagpur (470), etc, which reported the total COVID-19 cases 77,658, 37,629, 22,327, 1468, respectively, as of 1st July 2020. Mumbai has the highest population density and has the highest COVID-19 cases. Bherwani et al. (2020) also reported that the western region of Maharashtra which has a high population has recorded high COVID-19 confirmed cases, while the south region which has low population has evidently reported low infected cases. A similar picture was reported from Algeria (Kadi and Khelfaoui 2020), Turkey (Şahin 2020; Coşkun et al. 2020), Wuhan city of China (Pansini and Fornacca 2020), the US state and some Europian countries (Babbitt et al. 2020) where their population density creates the potential for higher person-to-person contagion rate, thus the higher rate of spread of this virus. Thus, this indicates that in densely populated cities, proximity living results in a lack of social distancing, which ultimately

Table 3 Nonlinear correlation (Kendall's correlation matrix) between meteorological, air quality, and COVID-19 parameters from 1st Jan to 3rd July 2020 in Maharashtra

Kendall's correlation matrix

	$PM_{2.5}$	PM10	NO	NO_2	NO_x	NH_3	CO	Ozone	Benz.	Tolu.	WS	RH	RF	Temp	DP	Infected	Recovery	Deaths
$PM_{2.5}$																		
PM10	0.82																	
NO	0.43	0.48																
NO_2	0.61	0.64	0.55															
NO_x	0.46	0.53	0.77	0.71														
NH_3	0.49	0.45	0.47	0.51	0.53													
CO	0.71	0.70	0.50	0.64	0.59	0.60												
Ozone	0.57	0.55	0.20	0.25	0.28	0.26	0.50											
Benzene	0.66	0.63	0.45	0.64	0.53	0.55	0.71	0.39										
Toluene	0.39	0.41	0.45	0.50	0.51	0.35	0.44	0.24	0.43									
WS	−0.03	−0.05	−0.29	−0.15	−0.28	−0.12	−0.05	0.13	−0.02	−0.15								
RH	−0.31	−0.36	−0.13	−0.26	−0.12	−0.07	−0.25	−0.44	−0.23	−0.16	−0.17							
RF	0.35	0.36	0.30	0.33	0.31	0.20	0.32	0.22	0.28	0.35	−0.07	−0.21						
Temp	−0.49	−0.45	−0.40	−0.50	−0.47	−0.51	−0.57	−0.32	−0.56	−0.35	0.05	0.05	−0.21					
DP	−0.59	−0.61	−0.37	−0.56	−0.42	−0.43	−0.62	−0.54	−0.58	−0.35	−0.06	0.38	−0.27	0.67				
Infected	−0.74	−0.71	−0.34	−0.58	−0.40	−0.49	−0.71	−0.58	−0.65	−0.41	−0.04	0.33	−0.32	0.62	0.73			
Recovery	−0.72	−0.70	−0.33	−0.55	−0.37	−0.48	−0.69	−0.60	−0.64	−0.39	−0.07	0.36	−0.30	0.58	0.71	0.89		
Deaths	−0.73	−0.72	−0.35	−0.56	−0.39	−0.50	−0.71	−0.58	−0.65	−0.41	−0.05	0.36	−0.32	0.58	0.72	0.90	0.91	

Temp: temperature; *DP*: dew point; *Benz.*: benzene; *RF*: rainfall; *WS*: wind speed; *Tolu.*: toluene; italic values denote statistical significance at the $p < 0.01$. Values exceeding ± 0.8 indicate a very strong correlation, ± 8 to ± 6 strong correlation, ± 6 to ± 4 moderate and ± 0.4 to ±0.1 weak correlation
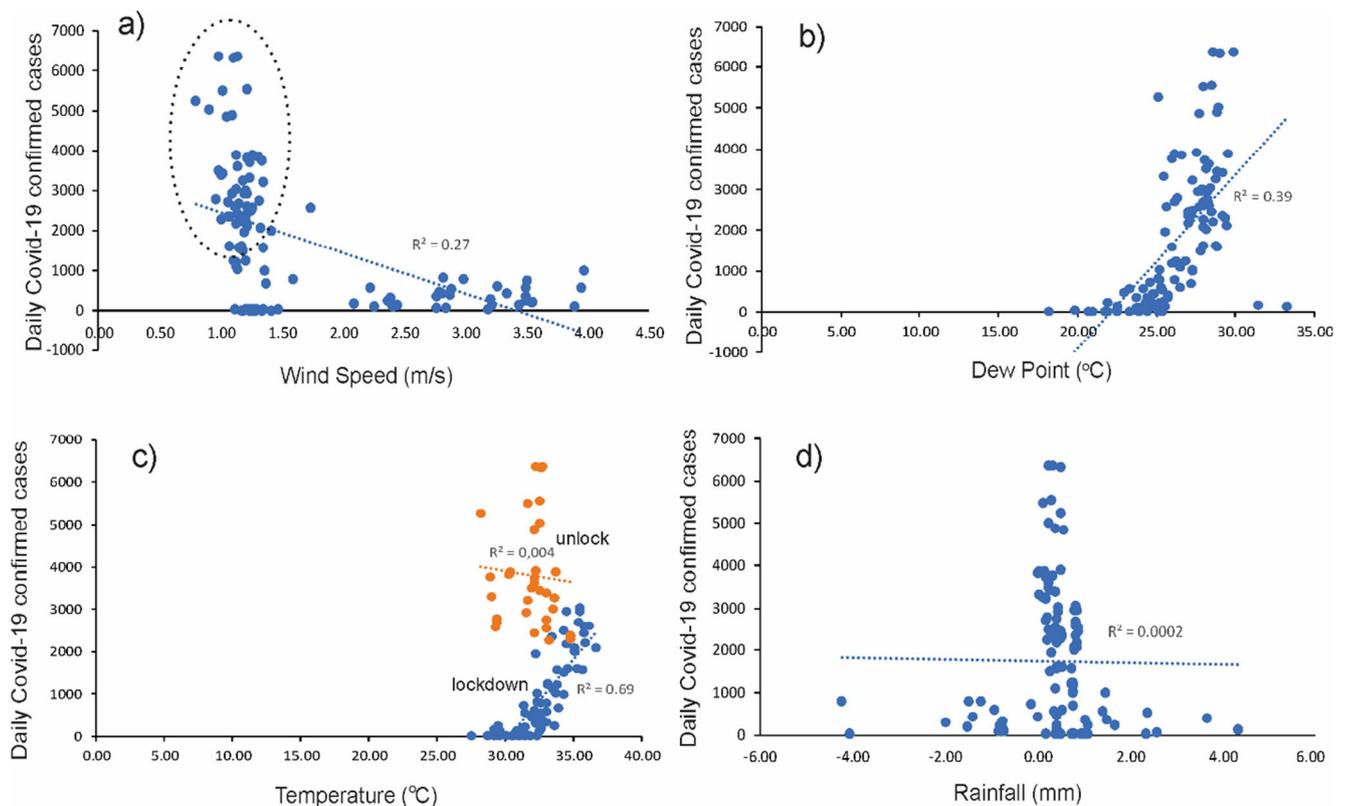
Fig. 6 Relationship between daily COVID-19 confirmed cases and wind speed (**a**), dew point (**b**), temperature (**c**), and rainfall (**d**) in Maharastra from 1 January to 3 July 2020

triggers the outbreak of this pandemic despite higher humidity and temperature which is unfavourable for the spreading of SARS-CoV-2 (Avhad et al. 2020; Coşkun et al. 2020). Similary, Gupta et al. (2020a) reported that past exposures to a high level of $PM_{2.5}$ over a long period are more prone to COVID-19 mortality ($p < 0.05$).

Furthermore, cities with high population density and size demand high energy, a large number of industries, and a huge number of vehicles. As a consequence, those cities will face most environmental challenges, especially air pollution (Maji et al. 2016). Continuous exposure to dirty air is known to increase unfavourable health impacts such as acute respiratory distress syndrome, which may have compromised their immune system and may be more susceptible to increase death rates from the disease (Xing et al. 2016; Kowalski and Konior 2020). Furthermore, cities experiencing serious air pollutions are linked to the faster spread of the COVID-19 as PMs can act as a carrier to transport the virus through the air in the form of aerosol (Comunian et al. 2020; Kowalski and Konior 2020). With this premise, we first studied the relationship of COVID-19 incidences with the air quality data from 1 Jan 2020 to 3 July 2020, which shows that the air pollutants have a strong negative correlation with COVID-19 incidences (Table 3). This relationship could be due to the impact of lockdown that drastically reduced most of the pollutants during this period; thus, they have little role in spreading COVID-

19 cases and other factors are more relevant for the spread of this virus. Secondly, when we evaluated the impact of past exposure to air pollutants ($PM_{2.5}$, PM_{10}, CO, and SO_2) based on the pre-lockdown concentration of the respective cities, it is found that $PM_{2.5}$ and PM_{10} are better correlated with the COVID-19 pandemic along with population density (Fig. 7), providing the fact that higher particulate matters in densely populated cities can lead to the spread of the virus as well as aggravate the chances of COVID-19 mortality. A similar association of $PM_{2.5}$ and population density with COVID-19 infection and mortality is highlighted by Pansini and Fornacca (2020) based on the data from eight countries such as China, Iran, Italy, Spain, France, Germany, the UK, and the USA. In another study, Wu et al. (2020a) in a nationwide study from the USA mentioned that long-term average exposure to $PM_{2.5}$ is a greater chance of increasing the risk of COVID-19 death. Gupta et al. (2020b) also reported the link between COVID-19 cases and past exposes to a high level of $PM_{2.5}$. Other studies also reported a significant positive correlation between the COVID-19 infections and air quality variables in China, the USA, Italy (Pansini and Fornacca 2020), and England (Travaglio et al. 2020). Zhu et al. (2020) reported a positive association between $PM_{2.5}$, PM_{10}, CO, NO_2, O_3, and COVID-19 confirmed cases. In Northern Italy, Setti et al. (2020) reported that PM_{10} pollution could be related to the spread of COVID-19. A similar observation was reported
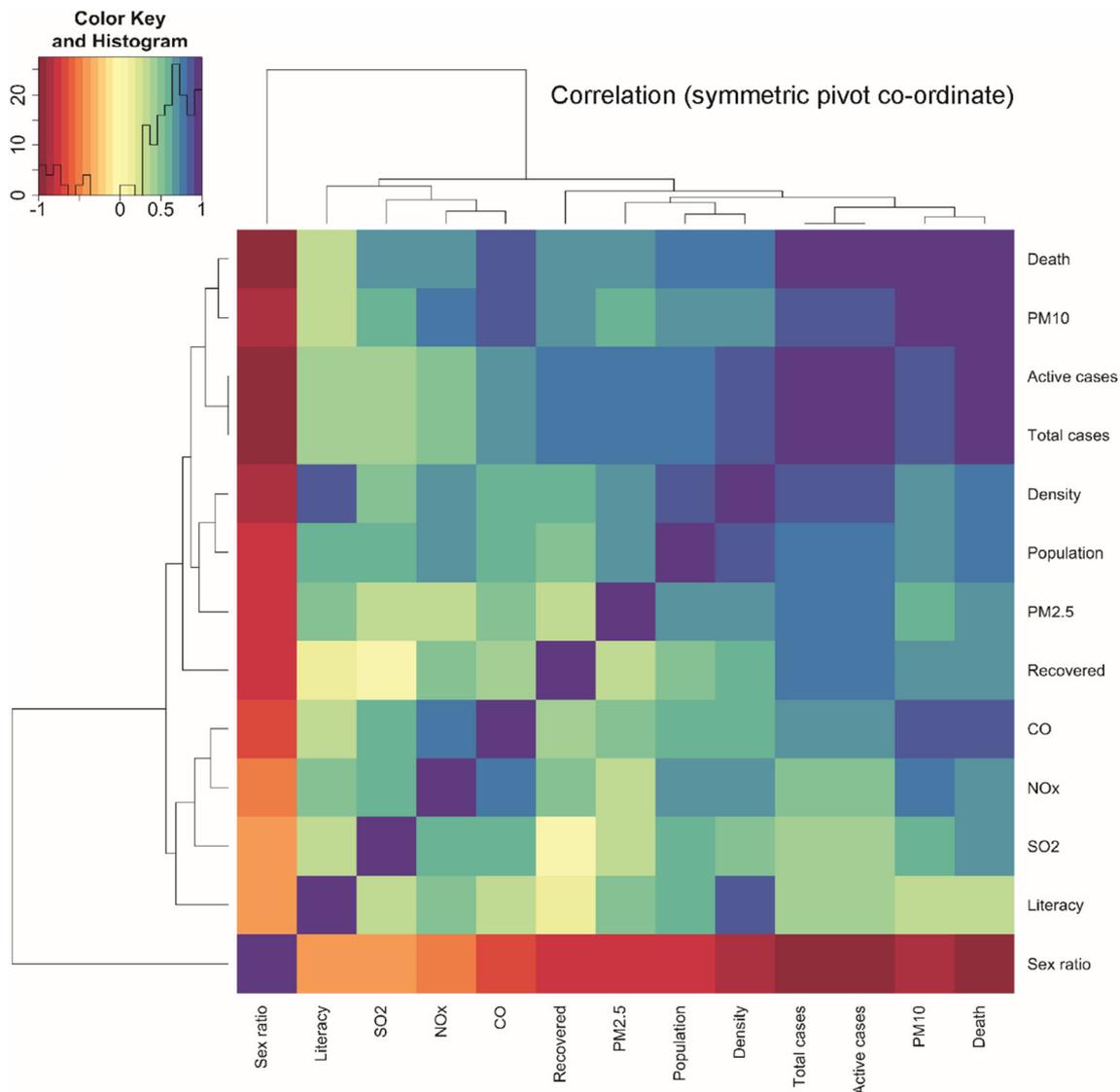
Fig. 7 Heat-plot showing the relation between different demographic and air quality parameters and COVID-19 incidences in Maharashtra. This is made based on city wise demographic, air quality, and COVID-19 data. For air quality data, maximum average concentration between the three pre-lockdown phases (PL$_1$, PL$_2$, and PL$_3$: Jan to March 2020) was taken. COVID-19 data was taken as on 3 July 2020

from Kuala Lumpur, Malaysia (Suhaimi et al. 2020). Thus, these studies are providing preliminary evidence that highly polluted cities should be more vigilant and take the necessary steps to increase their immune system to prevent COVID-19 mortality. However, further in-depth research is needed to elucidate the underlying mechanism and validate this finding.

Conclusion

The sharp decline in levels of PM$_{2.5}$, PM$_{10}$, NO$_2$, and CO during the COVID-19 lockdown in Maharashtra is due to strict restrictions on transportation, industries, and construction. Thus, this pandemic could be considered as a blessing in disguise. AQI remained 'satisfactory' during the lockdown phases and reduced further even post-lockdown due to the change in local weather patterns such as rainfall. Ground-level ozone and SO$_2$ were the least affected pollutants during this lockdown. A slight increase in the concentrations of gaseous pollutants like CO, NO, and SO$_2$ was again occured as the lockdown was relaxed. The AQI was continued to improve significantly during the unlock periods as a results of intermittent showers combined with the lockdown conditions. The relationship between meterological factors and COVID-19 incidences indicates that higher temperature and dew point cannot suppress the transmission of COVID-19. While, population density was found to be an important factor for the rapid spread of this virus in Maharashtra.

Furthermore, past exposure to high levels of $PM_{2.5}$ and PM_{10} may lead to a higher risk of COVID-19 mortality. These results show how multiple variables contribute to the spread of viruses and should be used to inform individuals about the proper use of safety measures when visiting more populated/industrial areas. The most important outcome of this study is to highlight to policymakers and the private sectors that purposeful actions to limit atmospheric pollution and even to attenuate population density in cities can have important implications for human survival. If we can alter our behaviour during a pandemic, and if that change in behaviour has such a positive result, then why cannot we formulate policy towards long-term survival and a better quality of life—let us use our knowledge wisely.

References

Avhad AS, Sutar PP, Mohite OT, pawar VS (2020) On the COVID-19 Pandemic in Indian State of Maharashtra: Forecasting & effect of different parameters. medRxiv preprint. https://doi.org/10.1101/2020.05.23.20111179

Babbitt D, Garland P, Johnson O (2020) Lived population density and the spread of COVID-19 arXiv:2005.01167v1 [physics.soc-ph] 3 May 2020.

Bera B, Bhattacharjee S, Shit PK, Sengupta N, Saha S (2020) Significant impacts of COVID-19 lockdown on urban air pollution in Kolkata (India) and amelioration of environmental health. Environ Dev Sustain. https://doi.org/10.1007/s10668-020-00898-5

Berman JD, Ebisu K (2020) Changes in U.S. air pollution during the COVID-19 pandemic. Sci Total Environ 739(15):139864

Bherwani H, Anjum S, Kumar S. et al. (2020) Understanding COVID-19 transmission through Bayesian probabilistic modeling and GIS-based Voronoi approach: a policy perspective. Environ Dev Sustain. https://doi.org/10.1007/s10668-020-00849-0

Brassey J, Heneghan C, Mahtani KR, Aronson JK (2020) Do weather conditions influence the transmission of the coronavirus (SARS-CoV-2)? CEBM. https://www.cebm.net/covid-19/do-weather-conditions-influence-the-transmission-of-the-coronavirus-sars-cov-2/

Chan KH, Peiris JS, Lam SY et al (2011) The effects of temperature and relative humidity on the viability of the SARS coronavirus. Adv Virol https://doi.org/10.1155/2011/734690

Comunian S, Dongo D, Milani C, Palestini P (2020) Air pollution and COVID-19: The role of particulate matter in the spread and increase of COVID-19's morbidity and mortality. Int J Environ Res Public Health 17 (12):4487

Coşkun H, Yıldırım N, Gündüz S (2020) The spread of COVID-19 virus through population density and wind in Turkey cities. Sci Total Environ. 751:141663

CPCB Parivesh Newsletter (2012) Benzene in air and its effect on human health, February, 2012. http://www.cpcbenvis.nic.in/newsletter/benzenefeb2002/feb02phy9.htm . Accessed 6 Jul 2020

CPCB (2014) National Air Quality Index Report. Central Pollution Control Board, New Delhi

CPCB (2020) Impact of lockdown (25th March to 15th April) on air quality. Ministry of Environment, Forest and Climate Change, Govt. of India, Delhi, 1–62. https://cpcb.nic.in/latest-cpcb.php. Accessed 6 Apr 2020

Cruz CJP, Ganly R, Li Z, Gietel-Basten S (2020) Exploring the young demographic profile of COVID-19 cases in Hong Kong: Evidence from migration and travel history data. PLoS ONE 15(6): e0235306. https://doi.org/10.1371/journal.pone.0235306

Cucinotta D, Vanelli M (2020) WHO declares COVID-19 a pandemic. Acta Bio-Medica: Atenei Parmensis 91:157

Dalziel BD, Kissler S, Gog JR, Viboud C, Bjørnstad ON, Metcalf CJE, Grenfell BT (2018) Urbanization and humidity shape the intensity of influenza epidemics in U.S. cities. Science 362:75–79

Dantas G, Siciliano B, França BB, Silva, CM, 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

Davis RE, Mcgregor G, Enfield KB (2016) Humidity: a review and primer on atmospheric moisture and human health. Environ Res 144(Pt A):106–116

Dutheil F, Baker SJ, Navel V (2020) COVID-19 as a factor influencing air pollution? Environ Pollut 263:114466. https://doi.org/10.1016/j.envpol.2020.114466

ESA (2020) https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-5P/Coronavirus_lockdown_leading_to_drop_in_pollution_across_Europe. Accessed 20 May 2020

Fang X, Xiao H, Sun H, Liu C, Zhang Z, Xie Y, Liang Y, Wang F (2020) Characteristics of Ground-Level Ozone from 2015 to 2018 in BTH Area, China. Atmosphere 11(2):130. https://doi.org/10.3390/atmos11020130

Ghosh N, Roy A, Bose D, Das N, Debsarkar A, Roy J (2020) COVID-19 Lockdown: lessons learnt using multiple air quality monitoring station data from Kolkata City in India [preprint]. https://doi.org/10.21203/rs.3.rs-43739/v1

Gorai A, Tchounwou P, Tuluri F (2016) Association between ambient air pollution and asthma prevalence in different population groups residing in eastern Texas, USA. Int J Environ Res Public Health 13: 378

Gupta S, Raghuwanshi GS, Chanda A (2020b) Effect of weather on COVID-19 spread in the US: A prediction model for India in 2020. Sci Total Environ 728:138960

Gupta A, Bherwani H, Gautam S, Anjum S, Musugu K, Kumar N, Anshul A, Kumar R (2020a) Air pollution aggravating COVID-19 lethality? Exploration in Asian cities using statistical models. Environ Dev Sustain. https://doi.org/10.1007/s10668-020-00878-9

Hamidi S, Sabouri S, Ewing R (2020) Does density aggravate the COVID-19 pandemic? J Am Plan Assoc. https://doi.org/10.1080/01944363.2020.1777891

Holtmann M, Jones M, Shah A, Holtmann G (2020) Low ambient temperatures are associated with more rapid spread of COVID-19 in the early phase of the endemic. Environ Res 186:109625. https://doi.org/10.1016/j.envres.2020.109625

Howell DC (2012) Statistical methods for psychology (8th edition). ISBN-13: 9781111835484, Publisher: Cengage Learning, Belmont, CA, 792

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 x:1–15 xxxx

Johns Hopkins University (2020) Coronavirus Resource Center. https://coronavirus.jhu.edu/map.html, Accessed date: 14 April 2020.

Kadi N, Khelfaoui M (2020) Population density, a factor in the spread of COVID-19 in Algeria: statistic study. Bull Natl Res Cent 44 (1):138

Kerimray A, Baimatova N, Ibragimova OP, Bukenov B, Kenessov B, Plotitsyn P et al (2020) Assessing air quality changes in large cities during COVID-19 lockdowns: the impacts of traffic urban conditions in Almaty, Kazakhstan. Sci Total Environ 730:1–8. https://doi.org/10.1016/j.scitotenv.2020.139179

Kowalski PA, Konior A (2020) Why air pollution is linked to a faster spread of coronavirus. Newsletter, https://airqualitynews.com/2020/04/09/why-air-pollution-is-linked-to-a-faster-spread-of-coronavirus/

Krecl P (2020) Drop in urban air pollution from COVID-19 pandemic: policy implications for the megacity of São Paulo. Environ Pollut 265:114883

Jamil T, Alam I, Gojobori T, Duarte CM (2020) No Evidence for temperature-dependence of the COVID-19 epidemic. Front Public Health. https://doi.org/10.3389/fpubh.2020.00436

Lawrence MG (2005) The relationship between relative humidity and the dewpoint temperature in moist air: A simple conversion and applications. Bull Am Meteorol Soc 86:225–233

Li H, Xu XL, Dai DW, Huang Z-Y, Ma Z, Guan YJ (2020) Air pollution and temperature are associated with increased COVID-19 incidence: a time series study. Int J Infect Dis 97:278–282

Li Y, Xiao C, Li J, Tang J, Geng X, Cui L et al (2018) Association between air pollution and upper respiratory tract infection in hospital outpatients aged 0–14 years in Hefei, China: a time series study. Public Health 156:92–100

Ma Y, Zhao Y, Liu J, He X, Wang B, Fu S, Yan J, Niu J, Zhou J, Luo B (2020) Effects of temperature variation and humidity on the death of COVID-19 in Wuhan, China. Sci Total Environ 724:138226. https://doi.org/10.1016/j.scitotenv.2020.138226

Mahato S, Pal S, Ghosh KG (2020) Effect of lockdown amid COVID-19 pandemic on air quality of the megacity Delhi, India. Sci Total Environ 730:139086

Maji KJ, Dikshit AK, Deshpande A (2016) Human health risk assessment due to air pollution in 10 urban cities in Maharashtra, India. Cogent Environ Sci 2(1):1193110

MPCB (2018) Air quality status of Maharashtra 2017-18. Maharashtra pollution control board, prepared by TERI. https://www.mpcb.gov.in/sites/default/files/focus-area-reports-documents/Air_Quality_Report_2017-18_29052019.pdf. Accessed 6 Dec 2020

MPCB (2019) Air quality status of Maharashtra 2018-19. Maharashtra pollution control board, prepared by TERI. https://www.teriin.org/sites/default/files/2019-06/Air_Quality_Report.pdf. Accessed 6 Jul 2020

Masum MH, Pal SK (2020) Statistical evaluation of selected air quality parameters influenced by COVID-19 lockdown. Global J Environ Sci Manage 6(SI):85–94

Menebo MM (2020) Temperature and precipitation associate with Covid-19 new daily cases: a correlation study between weather and Covid-19 pandemic in Oslo, Norway. Sci Total Environ 737:139659

Ministry of Home Affairs (MHA) (2020). Government of India issues orders prescribing lockdown for containment of COVID-19 epidemic in the country. Ministry of Home Affairs, Government of India, India. Data Accessed on 01.07.2020

MoHFW India (2020) MoHFW | Home [WWW Document]. https://www.mohfw.gov.in/513. Data accessed on 3rd May, 2020.

Muhmmad S, Long X, Salman M (2020) COVID-19 pandemic and environmental pollution: a blessing in disguise? Sci Total Environ 728:1–5. https://doi.org/10.1016/j.scitotenv.2020.138820

NASA (2020) Airborne Nitrogen Dioxide Plummets Over China [WWW Document]. URL https://earthobservatory.nasa.gov/images/146362/airborne-nitrogen-dioxide-plummets-518over-china. Data accessed on 29th April, 2020.

Navinya C, Patidar G, Phuleria HC (2020) Examining Effects of the COVID-19 National lockdown on ambient air quality across urban India. Aerosol Air Qual Res 20:1759–1771

Ogen Y (2020) Assessing nitrogen dioxide (NO2) levels as a contributing factor to coronavirus (COVID-19) fatality. Sci Total Environ 726:138605. https://doi.org/10.1016/j.scitotenv.2020.138605

Otmani A, Benchrif A, Tahri M, Bounakhla M, Chakir EM, Bouch M, Krombi M (2020) Impact of COVID-19 lockdown on PM10, SO_2 and NO_2 concentrations in Sale city (Morocco). Sci Total Environ 735:139541

Pani SK, Chantara S, Khamkaew C, Lee CT, Lin NH (2019) Biomass burning in the northern peninsular Southeast Asia: aerosol chemical profile and potential exposure. Atmos Res 224:180–195

Pani SK, Wang SH, Lin N-H, Chantara S, Lee CT, Thepnuan D (2020a) Black carbon over an urban atmosphere in northern peninsular Southeast Asia: characteristics, source apportionment, and associated health risks. Environ Pollut 259:113871

Pani SK, Lin NH, RavindraBabu S (2020b) Association of COVID-19 pandemic with meteorological parameters over Singapore. Sci Total Environ 740:140112

Pansini R, Fornacca D (2020) Higher virulence of COVID-19 in the air-polluted regions of eight severely affected countries. medRxiv preprint. https://doi.org/10.1101/2020.04.30.20086496

Pequeno P, Mendel B, Rosa C, Bosholn M, Souza JL et al. (2020) Air transportation, population density and temperature predict the spread of COVID-19 in Brazil. PeerJ 8:e9322

Qi H, Xiao S, Shi R et al (2020) Covid-19 transmission in Mainland China is associated with temperature and humidity: a timeseries analysis. Sci Total Environ 728:138778

R Core Team (2018) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna https://www.R-project.org

Sahoo PK, Chauhan AK, Mangla S, Pathak AK, Garg VK (2021) COVID-19 pandemic: an outlook on its impact on air quality and its association with environmental variables in major cities of Punjab and Chandigarh, India. Environ Forensic 22 (1)

Sajadi MM, Habibzadeh P, Vintzileos A, Shokouhi S, Miralles-Wilhelm F, Amoroso A (2020) Temperature, humidity, and latitude analysis to predict potential spread and seasonality for COVID-19. Available at SSRN; https://doi.org/10.2139/ssrn.3550308

Şahin M (2020) Impact of weather on COVID-19 pandemic in Turkey. Sci Total Environ 728:138810

Sahoo PK, Powell M, Mittal S, Garg, VK (2020) Is the transmission of novel coronavirus disease (COVID-19) weather dependent? J Air Waste Manag Assoc. https://doi.org/10.1080/10962247.2020.1823763

Setti L, Passarini F, de Gennaro G, Di Gilio A, Palmisani J, Buono P, Fornari G, Perrone M, Piazzalunga A, Barbieri P, Rizzo E, Miani A (2020) Evaluation of the potential relationship between particulate matter (PM) pollution and COVID-19 infection spread in Italy. http://www.simaonlus.it/wpsima/wp-content/uploads/2020/03/COVID_19_position-paper_ENG.pdf

Sharma S, Zhang M, Anshika Gao J, Zhang H, Kota SH (2020) Effect of restricted emissions during COVID-19 on air quality in India. Sci Total Environ 728:138878. https://doi.org/10.1016/j.scitotenv.2020.138878

Shi X, Brasseur GP (2020) The response in air quality to the reduction of Chinese economic activities during the COVID-19 outbreak. Geophys Res Lett 47(11):e2020GL088070

Shi P, Dong Y, Yan H, Li X, Zhao C, Liu W, et al. (2020) The impact of temperature and absolute humidity on the coronavirus disease 2019 (COVID-19) outbreak-evidence from China. medRxiv

Suhaimi NF, Jalaludin J, Latic MT (2020) Demystifying a possible relationship between COVID-19, air quality and meteorological factors: evidence from Kuala Lumpur, Malaysia. Aerosol Air Qual Res 20:1520–1529

Tan J, Mu L, Huang J, Yu S, Chen B, Yin J (2005) An initial investigation of the association between the SARS outbreak and weather: with the view of the environmental temperature and its variation. J Epidemiol Community Health 59:186–192. https://doi.org/10.1136/jech.2004.020180

Thomas (2020) The effect of weather on COVID-19 infection rate. https://www.news-medical.net/news/20200506/The-effect-of-weather-on-COVID-19-infection-rate.aspx. Accessed on 1st July 2020.

Tobías A, Carnerero C, Reche C, Massagué J, Via M, Minguillón MC, Alastuey A, Querol X (2020) Changes in air quality during the lockdown in Barcelona (Spain) one month into the SARS-CoV-2 epidemic. Sci Total Environ 726:138540

Tosepu R, Gunawan J, Savitri D et al (2020) Correlation between weather and COVID-19 pandemic in Jakarta, Indonesia. Sci Total Environ 725:138436

Travaglio M, Yu Y, Popovic R, Selley L, Leal NS, Martins M (2020) Links between air pollution and COVID-19 in England. medRxiv [preprint]. https://doi.org/10.1101/2020.04.16.20067405.

Vandini S, Corvaglia L, Alessandroni R, Aquilano G, Marsico C, Spinelli M, Lanari M, Faldella G (2013) Respiratory syncytial virus infection in infants and correlation with meteorological factors and air pollutants. Ital J Pediatr 39(1):1

Wang J, Tang K, Feng K, Lv W (2020) High temperature and high humidity reduce the transmission of COVID-19. Available at SSRN 3551767.

Ward MP, Xiao S, Zhang Z (2020) The role of climate during the COVID-19 epidemic in New South Wales, Australia. Transbound Emerg Dis. https://doi.org/10.1111/tbed.13631

WHO (2020) Coronavirus disease (COVID-19) pandemic. https://www.who.int/emergencies/diseases/novel-coronavirus-2019. Accessed 6 May 2020

Wu X, Nethery RC, Sabath BM, Braun D, Dominici F (2020a) Exposure to air pollution and COVID-19 mortality in the United States. medRxiv 2020.04.05.20054502. https://doi.org/10.1101/2020.04.05.20054502

Wu Y, Jing W, Liu J, Ma Q, Yuan J, Wang Y, Du M, Liu M (2020b) Effects of temperature and humidity on the daily new cases and new deaths of COVID-19 in 166 countries. Sci Total Environ 729:139051

Xie J, Zhu Y (2020) Association between ambient temperature and COVID-19 infection in 122 cities from China. Sci Total Environ 724:138201. https://doi.org/10.1016/j.scitotenv.2020.138201

Xing YF, Xu YH, Shi MH, Lian YX (2016) The impact of PM2.5 on the human respiratory system. J Thoracic Dis 8(1):e6

Xu K, Cui K, Young LH, Hsieh YK, Wang YF, Zhang J, Wan S (2020) Impact of the COVID-19 event on air quality in central China. Aerosol Air Qual Res 20:915–929. https://doi.org/10.4209/aaqr.2020.04.0150

Yao Y, Pan J, Liu Z, Meng X, Wang W, Kan H, Wang W (2020) No association of COVID-19 transmission with temperature or UV radiation in Chinese cities. Eur Respir J 55:2000517. https://doi.org/10.1183/13993003.00517-2020

Zhu Y, Xie J, Huang F, Cao L (2020) Association between short-term exposure to air pollution and COVID-19 infection: evidence from China. Sci Total Environ 727:138704

Zoran MA, Savastru RS, Savastru DM, Tautan MN (2020) Assessing the relationship between surface levels of PM2.5 and PM10 particulate matter impact on COVID-19 in Milan, Italy. Sci Total Environ 738:139825