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COVID-19 induced lockdown and decreasing particulate matter (PM10): An empirical investigation of an Asian megacity

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ABSTRACT

The air quality in the cities of developing countries is deteriorating with the proliferation of anthropogenic activities that add pollutant matters in the lower part of the troposphere. Particulate matter with an aerodynamic diameter lower than 10 μm (PM10) is considered one of the direct indicators of air quality in an urban area as it brings health morbidities. The article empirically investigates the role COVID-19 related lockdown has played in bringing down pollution level (PM10) in the megacity of Kolkata. It does so by taking account of PM10 level in three stages – pre, presage and complete-lockdown timelines. The extracted results show a significant declining trend (about 77% vis-a-vis the pre-lockdown period) with 95% of the geographical area under 100 μg/m³ and a strong fit with the station-based records. The feasibility and robustness showed by the remotely sensed data along with other earth observatory information for larger-scale pollution prevalence make its adoption imperative. Simultaneously, it becomes urgent in times of lockdown when the physical mobility of maintenance and research staff to stations is significantly curtailed. The work contributes to study on PM10 by its ability to replicate in examining cities of both the global north and global south.

1. Introduction

The novel Coronavirus Disease (COVID-19) has spread to every corner of the globe after originating in Wuhan, China (Gilbert et al., 2020; Sohrabi et al., 2020). The World Health Organization declared it a pandemic on 11th March 2020 (WHO, 2020a). The disease has mostly transmitted through the leading urban centers across the globe like New York, Paris, Mumbai, and London, aptly called the ‘gateway of COVID-19’, hinting at a positive correlation between city-size and COVID-19 cases (Stier et al., 2020). Thus, the pandemic that sutures our cities like never before has raised questions about their sustainability and future forms that they may adorn. With the adoption of ‘social distancing’, primarily the only possible way by which the disease can be allayed (Fong et al., 2020), it became urgent to lockdown regions and curtail human movement and contact. Naturally, the pollution levels during the lockdown period have shown considerable downfall (Cadotte, 2020; He et al., 2020; Huang et al., 2020; Mahato et al., 2020; Okyere et al., 2020) all over the globe. The experiential nature of it is evident when air pollution is reduced so much that the Himalayan peaks were visible for the first time in generations from Jalandhar in Punjab (Kaur and Banerji, 2020). Similar exuberance is reported from cities like Delhi (globally infamous for its pollution levels), São Paulo, Bangkok, and Bogotá (Ellis-Petersen et al., 2020).

The complete lockdown of India ensued from 25th March 2020 (Fig. 1). The lockdown scenario can be categorized into three
distinguishing phases, i) presage lockdown: 15th March to 21st March, the pre-situation of lockdown condition prevailing in the society after the first positive case was identified in the study area, it brings forth partial slowdown of people’s daily life whereas institutions were prevented from mass gathering, ii) citizen curfew: on 22nd March when the central government announced confinement of all activities and movement of people for a day, iii) complete lockdown: between 25th March and 30th May. The whole country had practiced social distancing and remained in home quarantine, with only availability of minimum resources and emergency services that extended for 68 days and was divided into four discrete phases.

The paper investigates the impact of lockdown due to COVID-19 on pollution level in the Kolkata Metropolitan Area (henceforth, KMA), the largest urban agglomeration in Eastern India. While investigating the effects, the article makes apt use of earth observatory data which includes remotely sensed images, spatial and non-spatial information, the in-situ instrument measured output pointing to the possibilities that they hold in gauging the impact with robustness and at a much larger scale.

2. Approach to the study

The negative impact of ambient aerosol including PM$_{10}$ is continuously increasing in India whereas it shows a declining trend on a global scale (Dey et al., 2012; Dey et al., 2018). The Central Pollution Control Board (CPCB) has 342 ground-based monitoring stations throughout the country. Their reading is based on high-volume air samples which are not sufficient enough for understanding PM$_{10}$ variability (Chitranshi et al., 2015; Dey et al., 2012; Dey and Di Girolamo, 2010) at a regional scale like Greater Kolkata.

The air quality assessment for a large region is a difficult task based on a few sample points (Vicente et al., 2018) as it gives a very coarse picture. Instead, the aerial view is most suitable for the purpose that captures the radiometric data of aerodynamic particulate matter on near-ground conditions. Fernández-Pacheco et al. (2018) stated that in conditions of dearth in continuous data for PM$_{10}$ estimation, remotely sensed information plays an important role in plugging the gap. A number of studies (Chitranshi et al., 2015; Chowdhury et al., 2019; Chu et al., 2003; Dey and Di Girolamo, 2010; Gupta et al., 2006; Gupta and Christopher, 2009, Gupta and Christopher, 2008; Hoff and Christopher, 2009; Kumar et al., 2008, Kumar et al., 2007; Lee et al., 2011; Liu et al., 2009; Singh et al., 2020; van Donkelaar et al., 2010; Wang and Christopher, 2003; Yap and Hashim, 2013) have successfully drawn on it in the last two decades to estimate the particulate matters in the troposphere using satellite based remotely sensed data. Most of these studies stretched for the meso to synoptic coverage area for vast geographical regions using 1 km $\times$ 1 km spatial resolution Moderate Resolution Imaging Spectro-radiometer (MODIS) or Visible Infrared Imaging Radiometer Suite (VIIRS) which retrieved the aerosol characteristics and its optical depth or thickness. But since the spatial resolution of MODIS and VIIRS are coarser than Landsat-8 (30 m) data (Alvarez-Mendoza et al., 2019; Olmanson et al., 2016) it is recently being widely used for estimating the aerosol optical depth through apt use of multifarious strategies and models (Alam et al., 2014; Alvarez-Mendoza et al., 2019; Bilal et al., 2013; Fernández-Pacheco et al., 2018; Mozafari et al., 2019; Saleh and Hasan, 2014).

3. Research objectives

The article aims at two interlinked research objectives-

Firstly, the empirical verification of reduction in air pollution in the Kolkata Metropolitan Area during the lockdown period that started on 25th March 2020.
Legend
(1) Dankuni Coal Complex
(2) Bidhannagar Waste Disposal
(3) Netaji Subhas Chandra Bose International Airport
(4) Bandel Thermal Power Station
(5) Bengal Steel Industries Limited
(6) Sankrail Industrial Park
(7) Bantala Leather Complex
(8) Titagarh Coal Power Station
(9) Budge Budge Jute Mill
(10) Phosphate Company Limited

Air Quality Monitoring Stations (WBPCB)
Kolkata Metropolitan Area
Kolkata Municipal Corporation
Hooghly River
Secondly, the remote sensing based extraction that we have employed to measure the change in PM$_{10}$ level in the metropolitan area brings novelty in a way that pollution can be measured more robustly and over a larger scale from alternative modes vis-à-vis the station-based point data.

4. Study area

Greater Kolkata is the third largest metropolitan area after Mumbai and Delhi (RGI, 2011) and popularly known as Kolkata Metropolitan Area or KMA (Fig. 2). Spanning around 1851.41 sq. km, it accommodates a total population of 14.06 million with 4 municipal corporations, 35 local municipalities, and 1 cantonment Board area. It also consists of 75 census towns, 6 outgrowths, and several rural settlement units.

Urban Kolkata is facing deteriorating air quality levels due to congestion and vehicular traffic (Das et al., 2006). Researchers have also reflected on the urgency of policy interventions in ensuring the breathability of the city (Majumdar et al., 2020). In a study by Karar and Gupta (2007) they have identified anthropogenic activities like solid waste dumping, vehicular emission, and coal combustion as the major source of PM$_{10}$ in residential areas and vehicular emission, coal combustion, and electroplating industries as major contributors of PM$_{10}$ at industrial sites in the vicinity of Kolkata. Based on a study by Air Quality Monitoring Committee (2018) under Government of West Bengal it is noticed that since November 2018, the air quality of Kolkata is declining sharply and has experienced the highest number of red category days in terms of air quality index. At times, the city’s air quality has become worse than Delhi’s (Haque et al., 2020) and is worsening day by day (Rudra, 2020). Government of West Bengal (Air Quality Monitoring Committee, 2018) in the National Green Tribunal (NGT) mentioned that vehicular emissions, emission from the construction sector, road dust re-suspension, industrial emission, trans-boundary pollution, etc. are continuing to pollute the city air.

As the study area is located in the tropical monsoonal climate, the PM$_{10}$ level varies from one season to the other. The prevailing of calm weather conditions during the end of November along with the weak turbulence due to the low incidence of solar energy, a huge concentration of PM$_{10}$ is received by the study area mostly from the Upper Ganga plain (Dey et al., 2018). Generally, this plain area receives less rainfall compared to the Gangetic delta and starts Rabi cultivation earlier. Thus, for field preparation, farmers burn agriculture residues and stubbles (Singh et al., 2020). The combination of super-micron size particles from this practice, with dust from the arid region and fossil fuel combustion there develops a chamber of atmospheric aerosol over the upper part of Indo-Ganga Belt (Dey and Di Girolamo, 2010). It creates a sharp gradient from Punjab plain to Ganga delta. The north-westerly wind pushes this aerosol layer (Dey et al., 2018) towards the deltaic land that leads to the concentration of PM$_{10}$ in Kolkata metropolitan area. The scanty rainfall, a light breeze in winter (December to February) entraps and sustains these particulates for a longer time supplemented by in situ emissions of aerosol that adds super-micron size particles in the lower part of the atmosphere. As a result, the situation aggravates in the winter months (Air Quality Monitoring Committee, 2018). Thus, PM$_{10}$ is considered as one of the non-attainment pollutants in National Green Tribunal in October 2018. After the vernal equinox there is increased incidence of solar radiation that generates vertical turbulence locally and light sea breeze blows over Kolkata, however in mid-April the PM$_{10}$ concentration has remained above 100 μg/m$^3$ for the last seven years (Air Quality Monitoring Committee, 2018). Although dry nor’westers contribute more aerosols but when accompanied with heavy shower aerosol particles are being swept out and amount of PM$_{10}$ concentration decreases after the end of April and early May.

Besides, Kolkata is called ‘the diesel capital of World’ (Centre for Science and Environment, 2016), for having a high number of diesel run commercial vehicles. The day time volume of motor vehicles (private cars and taxies) in Kolkata is recorded as nearly 2.6 Million and central Kolkata contributing the maximum share (Air Quality Monitoring Committee, 2018).

West Bengal Pollution Control Board (henceforth, WBPCB) is the nodal agency that monitors and regulates pollution over the megacity. To realise it, the board has installed 10 station-based pollution monitors and these all are shown in Fig. 2C. Based on location it is observed that a large part of the KMA is not covered by monitoring stations with most of them located in proximity to the metro-core areas i.e., Howrah, Bidhannagar, and Kolkata Municipal corporations.

5. Data set and methodology

5.1. Database

This study is carried out with the help of cloud free Landsat 8, Operational Land Imager (henceforth, OLI) images from the United States Geological Survey (USGS) path 138 and row 44 with a spatial resolution of 30 m. Using the WGS 84 datum and UTM zone north projection, the accessed Landsat imageries were pre-geo-referenced. The vehicle data has been extracted directly from the aerial view of Landsat and Copernicus images (based on synoptic time scale of google view) through the principle of geo-visualization considering all the seven components of image interpretation technique and user knowledge. Information about the particulate matter under 10 μm (PM$_{10}$) is extracted from three images belonging to three periods. The first image (set 1) is before the lockdown period (2nd February 2020) when the anthropogenic sources of particulate matters were in full swing; the second image (set 2) is that of the presage condition of lockdown (21st March 2020) when a 24-h public curfew/lockdown (on 22nd March 2020) was declared; and the final image (set 3) is the latest when the complete lockdown is underway (6th April 2020). It is assumed that as the winter is continuing in
February and pre-monsoon season approaches in late March over the lower Ganga plain the effect of atmospheric turbulence is very negligible to mix particulate matters in the mixed layer at a large extent. Besides, the presence of PM during February and pre-monsoon season only hints at the anthropogenic origin of the particulate matter. OLI data is also considered for the assessment of the built-up zone while the population density was computed using the latest Census data. For the validation of extracted PM level, information was obtained from the online data portal of the WBPCB and the official website of Regional Meteorological Centre (IMD), Kolkata. Other weather phenomena and air quality information was procured from the website of Kolkata US Consulate (https://aqicn.org/city/india/kolkata/us-consulate), West Bengal Paribesh App (https://apkcombo.com), and Air Quality Monitoring Stations, West Bengal Pollution Control Board (https://app.cpcbccr.com/AQI_India/). The detail of the data set is described below (Table 1).

### Table 1: Details of database used for PM$_{10}$ assessment and evaluation in KMA.

| Data type                     | Source                                                                 | Scale/Resolution                      | Purpose                                                                 |
|-------------------------------|------------------------------------------------------------------------|---------------------------------------|------------------------------------------------------------------------|
| COVID-19 cases in India       | https://www.worldometers.info/coronavirus/                             | National level                        | to visualise the Indian scenario along with Government initiatives and the social measures, to grapple the COVID-19 pandemic |
| Satellite image               | https://landsat.usgs.gov/                                              | Spatial resolution 30 × 30 m          | to measure PM$_{10}$ level, to assess the impact of various phases of lockdown on measured PM$_{10}$ in the study area, to understand the spatiality of built-up environment as a base information |
| Observed PM$_{10}$ (µg/m$^3$) data | Air Quality Monitoring Stations, West Bengal Pollution Control Board https://app.cpcbccr.com/AQI_India/ | Point data                            | to validate the model predicted PM$_{10}$ levels in KMA               |
| Weather variable (wind speed, wind direction, RH and rainfall) | Kolkata Regional Metrolological Centre, IMD, Kolkata portalrmc.gov.in/acwc/currentwx/all, Kolkata US Consulate (https://aqicn.org/city/india/kolkata/us-consulate) | Point data                            | to establish a relation between model results and micro-climate phenomenon |
| Total number of persons       | Census of India, 2011                                                 | Quantitative data                     | to use as a Base map and link with modelled result spatially           |
| Vehicle data                  | Google View, Copernicus Image                                          | Pixel-based data                      | to use as base information and link with vehicle scenario             |

#### 5.2. Conversion from DN value to top of the atmosphere (TOA) reflectance

The digital number (DN) value of a satellite band is the converted representation of actual reflectance from the surface. For the requirement of Top of Atmospheric reflectance (TOA) we need to transform the DN value to Total Atmospheric Radiance (TAR). The Reflectance Rescaling Coefficient (RRC) is required for the transformation. The metadata file provides RRC values. Regarding the transformation, the following equation is implemented for band 2 to 4 of Landsat 8 (Eq. 1).

$$\rho_{\lambda}^* = M_{\rho}^* Q_{\text{cal}} + A_{\rho}$$  \hspace{1cm} (1)

Where, $\rho_{\lambda}^*$ is the top of Atmosphere planetary reflectance. But, in this context, it should be noted that planetary reflectance at the top of the atmosphere does not involve sun angle correction. $M_{\rho}$ denotes the multiplicative rescaling factor for a specific band (REFLECTANCE.ADD_BAND.x, where x denotes the band number), $A_{\rho}$ is additive rescaling factor for a specific band (REFLECTANCE.ADD_BAND.x, where x defines band number), and $Q_{\text{cal}}$ is quantized calibrated pixel respectively.

#### 5.3. Sun angle correction

The TOA is not corrected for solar angle, which may have some deviated value due to changes in solar angle. Therefore, sun angle correction is an essential step for PM$_{10}$ calculation. The sun angle of the top reflection of the atmosphere is determined using the following formula for correction (Eq. 2).

$$\rho_{\lambda} = \frac{\rho_{\lambda}^*}{\cos(\theta_{SZ})} = \frac{\rho_{\lambda}^*}{\sin(\theta_{SE})}$$  \hspace{1cm} (2)

where, $\rho_{\lambda}$ is Top of Atmospheric (TOA) planetary reflectance, $\rho_{\lambda}^*$ Top of Atmosphere planetary reflectance without correction of solar angle, $\theta_{SZ}$ and $\theta_{SE}$ are the local angle of sun elevation and solar zenith angle (local) respectively. The solar elevation is implemented for the measurement of the solar zenith angle by applying Eq. 3.

$$\theta_{SE} = 90^\circ - \theta_{SZ}$$  \hspace{1cm} (3)

It is noted that pre-pixel solar angle data is essential for more appropriate reflection, which are not correctly available with metadata, which is substantiated with the...
5.4. Atmospheric correction

The goal of air correction is to eliminate the various atmospheric effects that affect the signal the sensors receive. For multi-spectral satellite imaging, there are several techniques and approaches. Equation 4 is applied for the measurement of land surface reflectance.

\[
\rho = \frac{\pi^2 (L_\lambda - L_p)^* d^2}{Tv^* \{ (ESUN_\lambda^* \cos \theta_{SZ}^* T_Z^*) + E_{down} \}}
\]

(4)

where, \( \rho \) denote the land surface reflectance, \( L_p \) is path radiance, \( L_\lambda \)is the top of atmospheric radiance, \( T_v \) is atmospheric transmittance in the viewing direction, \( T_Z \) is the atmospheric transmittance in the radiating direction, \( E_{down} \) defines the downwelling diffuse irradiance, \( ESUN_\lambda \) is the solar exo-atmospheric irradiances, and \( d \) is the distance between earth and sun.

Secondly, the removal of path radiance is a vital task for extracting the respiratory particulates from Landsat 8 OLI image. The Dark Object Subtraction method is currently the frequently used method for calculating Landsat 8 OLI data’s path radiance. The Dark Object Subtraction’s prime principle is determining the dark object. The path radiance is calculated as described by (Pal and Mandal, 2019; Sobrino et al., 2004).

\[
L_p = L_{min} - 0.01 * \frac{ESUN_\lambda^* \cos(\theta_{sz})}{\pi^2 d^2}
\]

(5)

where, \( L_p \) is path radiance, \( L_{min} \) denotes as radiance minimum band for a specific band (RADIANCE\_MINIMUM\_BAND\_x, where \( x \) denotes the band number), \( ESUN_\lambda \) is the solar exo-atmospheric irradiances, and \( d \) is the distance between earth and sun.

5.5. Computation of PM\(_{10}\) from Landsat 8 OLI image

The amount of electromagnetic radiation by the earth’s surface and from the atmosphere enables retrieving the column of aerosol by estimating the amount of aerosol optical thickness (AOT). In this present study, the estimation of PM\(_{10}\) from the OLI data was performed through the calculation of aerosol optical thickness and its relation with particulate matter. This attempt is also developed by following equations (Eq. 6 to 12). The atmospheric reflectance value is calculated by excluding the TOA and the reflectance of the surface. The AOT is calculated based on the a forementioned principle as Eq. 6.

\[
AOT(\lambda) = aoR(\lambda)
\]

(6)
Fig. 4. The daily mean PM$_{10}$ level for four stations (a) Rabindra Bharati University (b) Ghusuri (c) Victoria (d) Padmapukur.
Fig. 5. Spatiality of model generated PM$_{10}$ in study area with selected clusters in (a) pre lockdown, (b) presage lockdown, and (c) complete lockdown period.
$R(\lambda) = \rho a(\theta_{sz}, \theta_v, \phi)$

$$ao = \left(\frac{4\mu_o}{\omega_o\mu(a(\theta_{sz}, \theta_v, \phi))}\right)$$ (7)

where, $R(\lambda)$ denotes the atmospheric reflectance comparable to wavelength region ($\lambda$) for satellite, $Pa(\theta_{sz}, \theta_v, \phi)$ is the function of the aerosol scattering phase, $\theta_{sz}$ and $\theta_v$ are the solar and viewing zenith angle, $\phi$ is the relative azimuth angle, $\mu$ is the I cosines of the view directions, $\mu_o$ is cosines of the illumination directions, and $\omega_o$ is albedo sing-scattering.

This equation can be written as follows for the three bands;

$$AOT = aoR_{11} + a_1R_{21} + a_2R_{31}$$ (8)

where, $R_{11/2/3} = \text{atmospheric reflectance}$ ($1, 2, \text{ and } 3 \text{ comparable to wavelength region for satellite}$), denote the algorithm coefficient.

The aerosol optical thickness and particulate matter relationship are defined as a single homogeneous atmospheric layer comprising the spherical aerosol particles. (Koelemeijer et al., 2006) stated in the article that the concentration of aerosol mass at the lower atmosphere of the earth’s surface is obtained by drying sampled air.

$$PM = \frac{4}{3}\pi \rho \int r^3 n(r) dr$$ (9)

where, PM denotes the particulate matter, $r$ is the aerosol mass density, and $n(r)$ describes the aerosol size distribution under dry conditions.

The particulate matter (PM) is therefore predicted to be highly correlated with the aerosol optical thickness (AOT). The method for estimating particulate matter concentrations is developed by Nadzri et al. (2010) using the spectral aerosol optic thickness (AOT) recovery.

$$PM_{10} = aoR_{11} + a_1R_{21} + a_2R_{31}$$ (10)

To understand the spatial variation of PM$_{10}$ across the metropolitan area from the centre to the periphery, eight radial lines were designed at 45° intervals. For this purpose, computer-generated eight cross-sections of PM$_{10}$ in each angular direction are taken into account to show distance dependent variation of particulate matter in the three images.

5.6. Validation of computed data output

A statistical method is employed here to estimate the adequacy of modelled output with the observed data of WBPCB by employing coefficient of correlation i.e. normalised Covariance of $x$ and $y$. The scatter plot of the in-situ measured PM$_{10}$ value

| PM$_{10}$ Classes ($\mu g/m^3$) | Area in Percentage |
|---------------------------------|--------------------|
| Pre Lockdown (2/2/2020)        | Pressage Lockdown (21/3/2020) | Complete Lockdown (6/4/2020) |
| Less than 100                   | 0.0                 | 29.090                     | 94.351                    |
| 100–150                         | 0.0001              | 70.729                     | 5.541                     |
| 150–200                         | 99.292              | 0.163                      | 0.082                     |
| More than 200                   | 0.707               | 0.018                      | 0.027                     |

| PM$_{10}$ Value/Time             | Highest PM$_{10}$ Value ($\mu g/m^3$) | Lowest PM$_{10}$ Value ($\mu g/m^3$) | Wind Velocity (km/h) | Wind Direction | RH range (%) | Rainfall (mm) |
|---------------------------------|---------------------------------------|-------------------------------------|-----------------------|----------------|--------------|---------------|
| Pre Lockdown (2/2/2020)         | 307.98                                | 137.03                              | 2.5                   | S, SW          | 93–40        | Nil           |
| Pressage Lockdown (21/3/2020)   | 300.77                                | 81.31                               | 4.9                   | S, SE          | 81–31        | Nil           |
| Complete Lockdown (6/4/2020)    | 305.69                                | 32.51                               | 3–12                  | SW, S          | 94–48        | Nil           |
Table 4
Traffic volume at major intersections of Kolkata (based on synoptic time scale of google view).

| Crossing | Road (500 m buffer from crossing) | Number of Vehicle (January 13, 2020) | Total Grand Total | Number of Vehicle (March 27, 2020) | Total Grand Total |
|----------|-----------------------------------|--------------------------------------|-------------------|------------------------------------|-------------------|
|          | 2/3 wheeler | 4 wheeler | Minibus | Large Bus | Goods carrier | 2/3 wheeler | 4 wheeler | Minibus | Large Bus | Goods Carrier |
| Howrah Stn. | Station Road | 17 | 65 | 19 | 32 | 11 | 144 | 627 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 14 |
|          | Bamkim Setu Road | 61 | 81 | 19 | 53 | 7 | 221 | 0 | 5 | 0 | 0 | 0 | 1 | 6 |
|          | Howrah Basu Road | 10 | 57 | 20 | 9 | 11 | 107 | 0 | 5 | 0 | 0 | 0 | 1 | 6 |
|          | RBC Road | 7 | 140 | 0 | 0 | 8 | 155 | 0 | 2 | 0 | 0 | 0 | 0 | 2 |
| Rajbavan | Gostopal Sarani | 3 | 68 | 0 | 4 | 2 | 77 | 411 | 1 | 0 | 0 | 0 | 1 | 2 |
|          | Mayward Road | 7 | 34 | 4 | 13 | 2 | 60 | 1 | 3 | 0 | 0 | 0 | 1 | 9 |
|          | Rasmoni Avenue | 5 | 80 | 9 | 6 | 1 | 101 | 0 | 3 | 0 | 0 | 0 | 1 | 5 |
|          | M.E. Bithoo Road | 16 | 94 | 4 | 7 | 3 | 124 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| Central | B.B. Ganguly St. | 10 | 14 | 3 | 0 | 14 | 41 | 115 | 0 | 3 | 0 | 0 | 0 | 3 | 7 |
|          | Canning St. | 5 | 31 | 4 | 1 | 8 | 49 | 1 | 1 | 0 | 0 | 0 | 0 | 2 |
|          | Chittaranjann Avenue | 3 | 18 | 0 | 1 | 3 | 25 | 1 | 0 | 0 | 1 | 0 | 0 | 2 |
| Sovabazar | Sovabazar St. | 18 | 9 | 1 | 0 | 3 | 31 | 76 | 0 | 0 | 0 | 0 | 0 | 0 | 3 |
|          | Jatindromohan | 4 | 32 | 4 | 3 | 2 | 45 | 0 | 2 | 0 | 0 | 0 | 1 | 3 |
| Shyambazar | RG Kar Road | 11 | 21 | 7 | 3 | 5 | 47 | 160 | 1 | 4 | 0 | 0 | 0 | 0 | 5 | 14 |
|          | A.P. Chandra Road | 3 | 9 | 4 | 2 | 2 | 20 | 1 | 1 | 0 | 0 | 0 | 0 | 2 |
|          | Bidhan Sarani | 2 | 5 | 6 | 1 | 2 | 16 | 0 | 4 | 0 | 0 | 1 | 5 |
|          | Bhupendra Bose Road | 7 | 15 | 9 | 3 | 4 | 38 | 0 | 0 | 0 | 0 | 0 | 0 |
|          | B.T Road | 5 | 19 | 10 | 2 | 3 | 39 | 0 | 2 | 0 | 0 | 0 | 0 | 2 |
| Maniktala | Vivekananda Rd | 32 | 47 | 20 | 5 | 18 | 122 | 209 | 0 | 5 | 0 | 0 | 1 | 6 | 10 |
|          | A.P. Chandra Road | 11 | 38 | 18 | 8 | 12 | 87 | 1 | 3 | 0 | 0 | 0 | 0 | 4 |
| Sealdah Br | Parikshit Road | 6 | 28 | 10 | 6 | 14 | 64 | 214 | 0 | 2 | 0 | 0 | 0 | 2 | 8 |
|          | A/C Bose Road | 23 | 76 | 14 | 20 | 17 | 150 | 2 | 3 | 0 | 0 | 0 | 1 | 6 |
against the model-extracted value is correlated for all the ten stations. Besides, the slope of the trend line also ascertains the strength of their association. The coefficient of determination ($R^2$) is also estimated to explain model validation. To examine the relation of PM$_{10}$ concentration with the existing urban environment, the built-up nature of the study area is considered in this work, which is estimated by the following equation (Ahmed and Akter, 2017) in term of normalised difference built-up index (NDBI) (Eq. 13).

$$NDBI = \frac{SWIR - NIR}{SWIR + NIR}$$ (13)

Where, NDBI is normalised difference built-up index, SWIR is shortwave infrared and NIR is near infrared waveband of OLI data.

The ejection of PM$_{10}$ from the ground surface is also controlled by the intensity of the built-up structure and the population density (Fig. 3). They depict the signature of different anthropogenic activities that play an important role in the ejection of PM$_{10}$ in the lower part of the troposphere.

5.7. Extraction of active emission zone of PM$_{10}$

As the COVID-19 related lockdown has stalled the daily life activities and urban functions whereby regulate all mass transit systems in the whole country, the complete lockdown situation explicitly hint at imprints of anthropogenic activity in terms of aerosol generation along with the PM$_{10}$. So, the simple deviation between two successive result indicate the present scenario of PM$_{10}$ concentration either as active emission spots or declining spaces and these are estimated by the following equation.

$$Z_{Active} = V_{mod1} - V_{mod2}$$ (14)

Where, $Z_{Active}$ is emission zone, $V_{mod1}$ is modelled pixel value of data set 1 (pre-lockdown, data of 21st March 2020). $V_{mod2}$ is modelled pixel value of data set 2 (presage lockdown, data of 6th April 2020).

Thus, the positive extracted value of $Z_{Active}$ means an increase in PM$_{10}$ value that is associated with the presence of active emission process whereas, the negative value response means a declining condition of the particulate matter.

6. Result

6.1. Spatio-temporal scenario of PM$_{10}$ reduction

The PM$_{10}$ level in the KMA has considerably declined during the COVID-19 lockdown period. Four sample stations (Rabindra Bharati University, Ghusuri, Victoria, and Padmapukur) out of the ten are selected for conforming to the above said statement. Fig. 4 (a, b, c, and d) shows the daily mean PM$_{10}$ level for 2019 and 2020 categorized by three periods (pre-lockdown, presage-lockdown, and complete-lockdown). In all the four figures it is seen that the two graphs (of two different years) have nearly identical levels in the pre-Lockdown phase with intermittent spikes and in the presage period there is a steep hike in 2020 for all the four stations. This is attributed to transport behaviour just before the Citizen Curfew (22nd March 2020). As the announcement of the curfew was made, the public anxiously wanted to reach their places, which was coupled with students and others related to academia started going home after its closure on 15th March 2020. The spike falls steeply at the citizen curfew date. In the complete lockdown period till 30th April, the graph for 2020 is much lower than that of 2019 enabling indirect inference that lockdown episode consistently brought the level down. However, except at Rabindra Bharati University, the PM$_{10}$ level (for both the years) has remained more or less below the extreme tolerable limit of 100 $\mu$m$^2$/m$^3$ as identified by the red line. The smoothened graph shows a Confidence Interval (as a band of blue and red colour) for both the years. As observed for all the four stations, the confidence interval in the complete lockdown phase is much narrower for 2020 than for 2019. To express solidarity and respect towards the COVID fighters people used firecrackers on 5th April night, which consequently spiked the PM$_{10}$ concentration on the next day’s record. However, the PM$_{10}$ level for 2020 is more consistent and stable at a lower level than that of 2019 (with intermittent spikes and falls) owing to the restrictions on motor vehicles in KMA and its immediate surroundings.

Table 5
Data table of extracted and observed PM$_{10}$ value ($\mu$g/m$^3$) in different Air Quality Monitoring station in Kolkata Metropolitan Area (KMA).

| Name of air quality monitoring stations | Model generated PM$_{10}$ value ($\mu$g/m$^3$) | Observed PM$_{10}$ value ($\mu$g/m$^3$), WBPCB |
|----------------------------------------|-----------------------------------------------|-----------------------------------------------|
|                                        | 02/02/2020 21/03/2020 06/04/2020 | 02/02/2020 21/03/2020 06/04/2020 |
| Jadavpur, Kolkata                       | 170.31 94.00 68.47 | 106.00 83.00 59.00 |
| Rabindra Sarobar, Kolkata               | 180.54 103.47 84.36 | 125.00 63.00 93.00 |
| Ballygunge, Kolkata                     | 178.82 97.90 71.84 | 139.00 75.00 67.00 |
| Victoria, Kolkata                       | 177.26 95.89 78.30 | Data not found 88.00 63.00 |
| Fort William, Kolkata                   | 177.67 98.57 73.02 | 150.00 75.00 74.00 |
| Bidhannagar, Kolkata                    | 160.13 101.15 75.88 | 80.00 97.00 66.00 |
| Rabindra Bharati University, Kolkata    | 182.61 114.98 91.67 | 173.00 123.00 85.00 |
| Belur Math, Howrah                      | 162.35 95.95 65.34 | 81.00 94.00 52.00 |
| Ghusuri, Howrah                         | 170.21 104.62 73.00 | 105.00 101.00 73.00 |
| Padmapukur, Howrah                      | 177.84 115.81 95.00 | 151.00 119.00 94.00 |
Fig. 6. Distance decay relation of PM$_{10}$ in various direction (a) North, (b) South, (c) East, (d) North East, (e) North West, (f) South East, (g) South West, and (h) West.
Fig. 6. (continued).
Fig. 7. Scatter diagrams showing the relationship between Model Extracted PM$_{10}$ and Observed PM$_{10}$ (a) pre lockdown, (b) presage lockdown, and (c) complete lockdown period.

Fig. 5 shows the complete scenario of PM$_{10}$ and its spatial variability in the study area as extracted from the images. Except for the few isolated pockets, all the other settlement units have experienced a lowering of the concentrated amount in the lower part of the atmosphere during the first week of April. However, at the beginning of February (2nd February 2020), the leading urban units in KMA were enveloped in PM$_{10}$ with high concentration located (Fig. 5) on the south-eastern built-up corridor i.e., Bidhannagar and New town area; and few pockets of Baruipur, Sonarpur, Sankrail, and Dankuni area were marked as the high PM$_{10}$ zone. Owing to the geographical and locational attribute, the boundary layer over these locations pulled in a huge amount of aerosol in late winter seasons and trapped it for a longer time. With respect to Fig. 5, it is emphasized that the noticeable concentration of this particulate matter is more in the high built-up region. From the model generated output, it is found that most of the area is under 150–200 $\mu$g/m$^3$ particulate matter concentration having an aerodynamic diameter of less than 10 $\mu$m (Table 2). The lowest amount is estimated at 137.03 $\mu$g/m$^3$, which is observed in very small pockets, and almost 7% of the total area has more than 200 $\mu$g/m$^3$ concentration, which is poor in quality and detrimental to comfortable breathing (Table 3). According to the Central Pollution Control Board, PM$_{10}$ value over 100 $\mu$g/m$^3$ is considered very dangerous for humans and animals, and influences both the weather phenomenon and the environment alike. After 15th March 2020 the partial lockdown to combat COVID-19 was declared by the state government (shutting down institutions of mass gathering, for instance, schools, colleges, and universities) and the first positive case was detected the very next day (on 16th March). The Government of West Bengal mandated employees to work from home and few of the multinational corporate houses and leading companies also asked their employees to follow the same to arrest COVID-19 from spreading. During the lock down period, the traffic volume has declined by between 91% and 97% at the major crossing points of the core city (Table 4). Consequently, the minimum value of PM$_{10}$ fell to 81.31 $\mu$g/m$^3$, while in some areas it went to as high as 300.37 $\mu$g/m$^3$ (Table 5). However, most of the area in KMA had PM$_{10}$ under 150 $\mu$g/m$^3$ on 21st March 2020. After the completion of thirteen days of complete lockdown the concentration of PM$_{10}$ all over the study area is lower on 6th April; almost 94% area of KMA had a satisfactory condition with less than 100 $\mu$g/m$^3$, and the lowest amount is estimated at 32.51 $\mu$g/m$^3$. During this phase of lockdown, the transport through all mode was fully suspended and human mobility was remarkably reduced (Government of West Bengal, 2020). The close inspection of all cross-sections (Fig. 6 a-h) shown as the linear trend of the particulate matter’s spatial concentration depicts the rapid fall of PM$_{10}$ concentration in data set 3. Considering all the sections, the average trend line of PM$_{10}$ is under 100 $\mu$g/m$^3$ while it is above 100 $\mu$g/m$^3$ on 21st March 2020. Similarly, it is excessively high for data set 1, experiencing the same in the first week of February for the last few years. Except for north and northwest sections, all others have a slightly declining concentration of the particulate matter towards periphery from the metro centre. It happens because all along these six lines there is a decreasing trend of the built-up area following the distance-decay function. Whereas, north (towards Bandel) and north-western (towards Dankuni) section are characterised by old urban and continuous urban patches with several industrial complexes and its allied activities and where works for infrastructural development is completely suspended and human mobility was remarkably reduced (Government of West Bengal, 2020). The close inspection of all cross-sections (Fig. 6 a-h) shown as the linear trend of the particulate matter’s spatial concentration depicts the rapid fall of PM$_{10}$ concentration in data set 3. Considering all the sections, the average trend line of PM$_{10}$ is under 100 $\mu$g/m$^3$ while it is above 100 $\mu$g/m$^3$ on 21st March 2020. Similarly, it is excessively high for data set 1, experiencing the same in the first week of February for the last few years. Except for north and northwest sections, all others have a slightly declining concentration of the particulate matter towards periphery from the metro centre. It happens because all along these six lines there is a decreasing trend of the built-up area following the distance-decay function. Whereas, north (towards Bandel) and north-western (towards Dankuni) section are characterised by old and continuous urban patches with several industrial complexes and its allied activities and where works for infrastructural development is regularly practiced. Thus, these two sections depicted an increasing trend of PM$_{10}$ level towards the periphery for data set 3. Coal-based thermal power plant at Bandel and Industrial hubs at Dankuni are the major sources of PM$_{10}$. However, due to the COVID-19 lockdown, most of the activities were closed for a long time although few emergency plants and workshops were functioning during this period. The data of 6th April shows that there is a negligible increase in PM$_{10}$ concentration. Due to the paucity of in-situ measurement effort throughout the KMA, only ten station data have to be considered for the validation of model-extracted estimation as shown in Table 5. Besides, all these stations are maintained by WBPCB and located in and around the proximity of the metro-city, so a vast area is situated outside the monitoring range of the instrument. Based on the linearity of association ($Y_c$) between model extracted data and WBPCB observed information (Fig. 7 a-c) it is found that all three sets are positively associated with a positive regression coefficient. The validity of the model output is confirmed by the regression coefficients. In data set 1, the deviation of scatter points from the $Y_c$ value is comparatively more and has mild divergent compared to other data sets however all the sets have a more or less same slope of regression. On the other hand, the coefficient of determination ($R^2$) value (Fig. 7 a-c) for pre-lockdown, presage-lockdown, and complete-lockdown phases (0.855, 0.839 and 0.857, respectively) is significantly accepted for its good predictability and explanation of the model. The result of PM$_{10}$ concentration in presage lockdown (on 21st March data i.e. set 2) and complete lockdown (6th April data i.e. set 3) is used for the estimation of active emission of PM$_{10}$ by Eq. 14. The extracted results show a significant declining trend (about 77% vis-a-vis the pre-lockdown period) with 95% of the geographical area under 100 $\mu$g/m$^3$ and a strong fit with the station-based records. This approach can be applied to estimate PM$_{10}$ for any compact urban region’s environment with slight variation.

6.2. Presence of active emission spots

The figure (Fig. 8) shows the presence of emission or sequestration location during the lockdown period, which is prepared based on Eq. 14. Only 0.35% area (small and isolated spots) has shown the increasing nature of PM$_{10}$. It is identified in the east of Dankuni area where emergency and essential services like the operation of carbonization plant is still functional that produces solid smokeless fuel; there is also a presence of a large milk plant (Mother Dairy), electric locomotive assembly and ancillary unit plant, and diesel locomotive factory. More than 99% area of KMA shows a declining PM$_{10}$ at the lower part of the atmosphere, out of which moderate, high, and very high decreasing areas estimated to have occupied 36.38%, 36.79%, and 8.86% area, respectively. Bidhannagar (popularly known as Salt Lake), Bantala, Baranagar, North Dum Dum, Garden Reach, Dhulagarh, Sankrail, and Uluberia areas show declining PM$_{10}$ value during COVID-19 episode due to temporary lockdown of the factories and small-scale industries along with other...
Fig. 8. Zone of PM$_{10}$ reduction and spot of active anthropogenic emissions in KMA.
choking infrastructural activities. The East Kolkata Wetlands, a Ramsar site, located in the western periphery of the metro center also show a diminution of these matters because of suspended development works and infrastructural headway (Haque, 2020). Besides, some of the spots with a low decrease in PM$_{10}$ levels are estimated to have occupied over 17.61% of the total KMA area. These areas have open space/bare ground or dry vegetated land cover with land use practices that naturally generate PM$_{10}$.

7. Discussion and conclusion

According to an estimate, around 29% of lung cancer deaths, 24% stroke deaths, 25% cardiac disease death, and 43% other lung disease are reportedly caused by air pollution (WHO, 2020b). Besides, air pollution also causes 26% of deaths due to respiratory illness, 25% deaths from Chronic Obstructive Pulmonary Disease (COPD), and approximately 17% of deaths from ischemic heart stroke (WHO, 2020c). At this point, it should be noted that for those with chronic respiratory and cardiovascular disorders, the COVID-19 death rate is significantly higher. Thus, air pollution can be seen as a secondary, but crucial, factor in such mortalities. Besides, it is directly correlated with the number of COVID-19 deaths in a study on China (Yao et al., 2020). Thus, with all the anthropogenic sources of PM$_{10}$ closed due to lockdown, the pollution levels have not only dropped by a considerable degree but its decrease may also bring down the cases in times to come.

As shown in the study, the level of PM$_{10}$ has decreased by a large margin across the KMA and especially in and around the Kolkata city. When matched with the station-based records, the results correlated very significantly. Thus, on the face of COVID-19 related lockdown, we are experiencing a cleaner air where the air shed dynamics and decreasing pattern of the particulate matter rates is in harmony with those happening around the globe (Cadotte, 2020; He et al., 2020). However, the temporal variation in pollution levels in the pre, presage, and complete-lockdown period is a novel exercise that this article has endeavoured. It is in this regard, that the article empirically shows how the pollution levels have changed in one of the largest megacities of South Asia. Secondly, the article also has a policy undertone in emphasizing on the role remote sensing technology can play to monitor and regulate pollution levels when there is a dearth of expanded infrastructural support on the ground. And, even if there are few stations, they seldom give data beyond the immediate environment of the station. Thus, with ten stations monitoring a megacity of 1900 sq. km. it becomes imperative that an alternative mechanism is thought over and adopted. This gets more urgent and relevant when the data obtained from remote sensing fits exactly with the station-based data. Besides, when the maintenance of such stations becomes a challenging job due to absolute restriction on people’s movement, this alternative technology comes handy for monitoring and regulating the pollution levels of a megacity.

The results and its significant correlation with station-based readings prompt urgent adoption of remote sensing technology to monitor pollution levels, which is capable of giving robust results at a much larger scale. The study contributes to a plethora of studies on pollution by its ability to show the potential of its replication in studying cities of both the global north and global south.

CRediT authorship contribution statement

Amiya Gayen: Conceptualization, Data curation, Methodology, Software, Visualization. Sk. Mafizul Haque: Writing - original draft, Visualization, Supervision. Swasti Vardhan Mishra: Writing - original draft, Visualization.

Declaration of Competing Interest

The authors declare no competing interests.

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