JSR Publications

Available Online

J. Sci. Res. **15** (2), 335-349 (2023)

JOURNAL OF SCIENTIFIC RESEARCH

www.banglajol.info/index.php/JSR

Spatial and Temporal Variability of $PM_{2.5}$, PM_{10} and BC Aerosols over Tropical Megacity Bengaluru, India

M. Shivkumar[1*], T. S. Pranesha[2], K. R. Sudhindra[1], D. M. Chate[3], G. Beig[4]

[1]Department of Electronics and Communication Engineering, BMS College of Engineering, Bengaluru-560019, India

[2]Department of Physics, BMS College of Engineering, Bengaluru-560019, India

[3]Centre for Development of Advanced Computing, Pune-411008, India

[4]National Institute of Advanced Studies, Bengaluru-560012, India

Received 28 August 2022, accepted in final revised form 8 February 2023

Abstract

$PM_{2.5}$, PM_{10} mass levels at six and BC levels at one station were monitored at the tropical megacity, Bengaluru, India, for the year 2019. The annual average levels of $PM_{2.5}$, PM_{10} and BC were 31, 73 and 2.72 µg/m^3 respectively. $PM_{2.5}$ levels were within the Indian National Ambient Air Quality Standard (INAAQS) value of 40 µg/m^3 whereas that of PM_{10} exceeded INAAQS level of 60 µg/m^3 for the year 2019 for all six stations. The season-wise diurnal variability of PM and BC shows bimodal peaks, first one in the morning and the second one in the late evening hours in all the stations. These peaks correspond to rush traffic hours and lower PBL height. The correlation analysis of PM and BC with meteorological parameters is presented. The data are also analysed for the Deepavali festival. The $PM_{2.5}$ levels in festival have doubled, PM_{10} levels increased by more than 50 %, while BC showed marginal increase. Further, the night-time levels of PM and BC were higher than the daytime during the festival. The health risk assessment using Air Q+ for the city of Bengaluru for 2019 shows highest PM exposure risk to ischemic heart disease.

Keywords: Particulate matter; Black carbon; Deepavali.

doi: http://dx.doi.org/10.3329/jsr.v15i2.61403 J. Sci. Res. **15** (2), 335-349 (2023)

1. Introduction

Particulate Matters (PM) are solid and liquid particles present in the atmosphere. The sources of PM are both natural and anthropogenic. The PM has a wide size spectrum, and their chemical compositions vary considerably. In addition to being directly released into the atmosphere by sources, few PM is produced by the process of conversion from gas-to-particle. PM are classified based on particle size. Fine particles are those with a diameter < 2.5 µm represented as $PM_{2.5}$, whereas coarse ones have a diameter of 2.5 to 10 µm represented as PM_{10}. PM get transported over long distances and have residence times

* *Corresponding author*: mshivu9@gmail.com

varying from days to months. $PM_{2.5}$ plays an important role in cloud formation, Earth-atmosphere radiation budget, and public health [1-3].

PM is known to cause many health issues. Inhalation of particles causes changes in the respiratory airway and weaken the pulmonary function, which may lead to cardio-respiratory problems or lung malignancy and hence may prove fatal. In the PM factions, PM_{10} leads to respiratory problems, and $PM_{2.5}$ leads to cardiovascular problems, which may cause death [4-6]. International Agency for Research on Cancer (IARC) has classified $PM_{2.5}$ as carcinogenic [7].

Black carbon (BC) is part of fine particulate air pollution, which contributes to changes in radiative forcing, thus playing a role in climate change [8]. BC is a short-lived aerosol species with a lifetime of days to weeks after being released into the atmosphere. BC affects climate, agriculture, and public health both directly and indirectly [9]. BC is often the result of incomplete fossil and bio-fuels combustion [10-12]. In urban air, BC constitutes ~5–15 % of $PM_{2.5}$ [13]. BC being absorbing aerosol influences many atmospheric processes leading to changes in precipitation [14].

In Bengaluru city, the continuous real-time observations of particulate matter and trace gases with meteorological variables were carried out at B M S College of Engineering (BMSCE) campus under the project MAPAN (Modeling Atmospheric Pollutants and Networking) of the Indian Institute of Tropical Meteorology (IITM) supported by the Ministry of Earth Science (MoES). The CPCB (Central Pollution Control Board) has also installed many Air Quality Monitoring Stations at different places in Bengaluru. The city of Bengaluru (120 58' N; 770 34' E; average 900 m elevation above sea level) is the state capital of Karnataka and the leading IT industry hub in India. With 11.5 million people, Bengaluru is the third city in India by population after Delhi and Mumbai. Its population has seen substantial growth of 13.2 % over the last decade [15]. A detailed description of the BMSCE site and urbanization of Bengaluru is presented by Shivkumar *et al.* [16], Dhanya *et al.* [17], and Gopi *et al.* [18]. Urbanization is the key factor that plays an important role in the increase in the levels of PM and BC [19,20].

In different parts of the world, New Year is celebrated by bursting the crackers e. g. Sky Fest in Ireland [21]. Deepavali is a famous festival celebrated in several parts of India, and the celebration involves the burning of firecrackers. [22]. The burning of crackers results in the emission of harmful compounds into the atmosphere [23]. Many researchers have highlighted that human health risks are linked to the usage of firecrackers [24]. The respiratory and cardiovascular disorders may be due to the episodic high levels of PM in the ambient air [25].

In the current study, the analysis of data of $PM_{2.5}$, $PM_{10,}$ and BC, as well as the meteorological variables continuously monitored for the city of Bengaluru, India, from January 2019–December 2019 at six different stations, are presented. Two data sets are utilized in this study. The data of PM and BC continuously monitored at the BMSCE campus under the MAPAN project is analyzed for temporal variability. The Central Pollution Control Board (CPCB) archived data of PM at five stations Bapuji Nagar (busy road), Jayanagar (residential and commercial), Hebbal (airport road), Hombegowda Nagar

(green canopy), and Silk Board (traffic congestion area) across the city are used for spatial distribution. The data of all these CPCB locations are archived hourly, daily, and monthly on the website of CPCB (https://app.cpcbccr.com/ccr/#/caaqm-dashboard-all/caaqm-landing/data). The season-wise diurnal and monthly variability of PM factions and BC at Bengaluru is also examined. In addition, the effect of the planetary boundary layer (PBL), ventilation coefficient (VC), and meteorological factors on levels of PM are also presented. The data of the Deepavali festival at different stations of Bengaluru for the year 2019 are analyzed. Health risk assessment due to exposure to PM is done for the city of Bengaluru. Premature mortalities due to PM linked with Ischemic Heart Disease (IHD), Chronic Obstructive Pulmonary Disease (COPD), Cerebrovascular Disease (CEV, Stroke), Lung Cancer (LC) in adults, and Acute Lower Respiratory Illness (ALRI) in children are estimated.

2. Instrumentation

Beta Attenuation Monitor was used to measure the level of PM. This device functions on beta ray attenuation.The AQMS at the BMSCE campus and those operated by CPCB work on the same principle. The BC mass level was measured using a seven-wavelength Aethalometer (Model-AE-31, Magee Scientific Company, Berkley, CA, USA). The measurement technique and the detailed descriptions of the instruments are available in Hansen [26]. An Automatic Weather Station (AWS), also installed at the observational site, measured the meteorological parameters. The data were archived for the year 2019 (January to December). Suitable averaging is done for further analysis.

3. Daily Time Series and Annual Levels of PM

The daily time series of $PM_{2.5}$ and PM_{10} are presented in Figs. 1a and 1b for the year 2019. The daily average values observed at all six stations are comparable. The daily average values show large fluctuations. Such large fluctuations are reported by many previous studies of PM [16]. In general, the large fluctuations in daily concentrations are attributed to changes in weather conditions.

The annual mean level of $PM_{2.5}$ in Bengaluru during 2019 is 31 $\mu g/m^{3,}$ which is below the INAAQS (Indian National Ambient Air Quality Standards) threshold of 40 $\mu g/m^3$, whereas, in the case of $PM_{10,}$ the annual mean level is 73 $\mu g/m^3$ which exceeds the INAAQS limit of 60 $\mu g/m^3$. The $PM_{2.5}$ levels of the BMSCE campus for the year 2015 were observed to be 28± 11 $\mu g/m^3$ [17]. The measured levels of $PM_{2.5}$ and PM_{10} in Bengaluru for 2019 were less than those reported for Delhi [27]. The authors attribute the higher levels in Delhi to vehicular emissions. Similar observations are reported from Chennai city for the years 2001-2004. The mean mass values of $PM_{2.5}$ and PM_{10} in Chennai are reported to vary between 42–46 $\mu g/m^3$ and 145–169 $\mu g/m^3$, respectively [28]. The yearly mean levels of $PM_{2.5}$ and PM_{10} were 80–90 $\mu g/m^3$ and 234–278 $\mu g/m^3$, respectively, from the measurements conducted at Agra, a semi-urban location [29]. Similar mass levels of $PM_{2.5}$ and PM_{10} have been reported from northern parts of India

[30]. Pope *et al.* [31] have reported PM measurements from the tropical city of Nairobi, Kenya. The levels of $PM_{2.5}$ and PM_{10} in Nairobi ranged from 11-21 µg/m^3 and 26-59 µg/m^3 for the period May 2016 to Jan 2017. In the extratropical city of Seoul, South Korea, the levels of $PM_{2.5}$ and PM_{10} are observed to be 26.6 ± 12 µg/m^3 and 45.0 ± 20.4 µg/m^3, respectively. The comparison of average levels of $PM_{2.5}$ and PM_{10} for all the stations in Bengaluru and other stations of India, tropical and extratropical stations of other countries, are listed in Table 1.

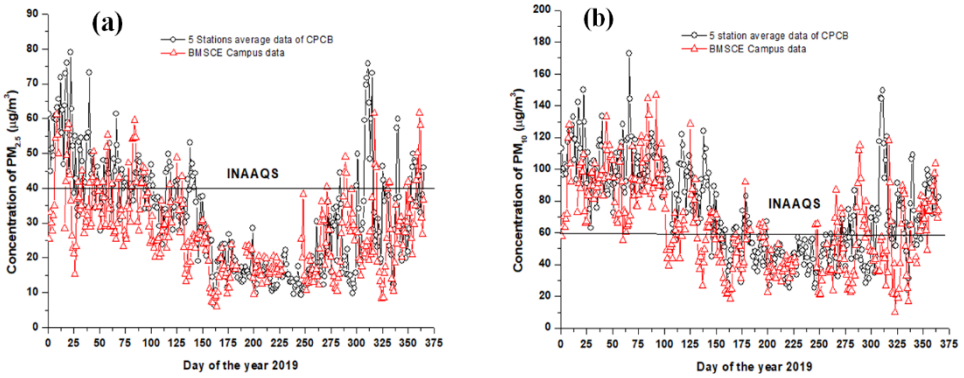

Fig. 1. Time series of $PM_{2.5}$ and PM_{10} at Bengaluru for the year 2019.

Table 1. Comparison of annual average mass levels of PM at Bengaluru with several stations in India and other countries.

City	Observational period	PM Levels, µg/m^3		Research group
		$PM_{2.5}$	PM_{10}	
Bengaluru	Jan 2019-Dec 2019	31	73	Present
Delhi	Dec 2010- Nov 2011	240	90	[27]
Agra	April 2010- June 2010	80-90	234-278	[29]
Chennai	2001-2004	42-46	145-169	[28]
Nairobi, Kenya	May 2016 – Jan 2017	11-21	26-59	[31]
Caraga State University, Ampayon, Butuan	2014-2020	8.7 ± 3.9	24.3±12.0	[32]
Ho Chi Minh City, Vietnam	Mar 2017-Mar 2018	39.1±14.9	51.5±18.2	[33]
Seoul, South Korea	2013	26.6 ± 12.6	45.0 ± 20.4	[34]
Athens (Aristotelous Street), Greece	1 Jun1999-31 May 2000	41	75.5	[35]
Darussalam, Mirpur, Dhaka Bangladesh	October 2016 to September 2017	85.41	145.78	[36]

4. Diurnal and Seasonal Variation of PM

The diurnal variability of $PM_{2.5}$ and PM_{10} are analyzed seasonally for the year 2019 and are shown in Figs. 2a and 2b. In India, the seasons are categorized as summer (March-May), monsoon (June-September), post-monsoon (October-November), and winter (December-February). The hourly mean of $PM_{2.5}$, PM_{10}, and BC mass levels shows significant diurnal variation. The distinct feature of diurnal variation is the appearance of

two peaks in the mass level–the first one between 7-9 hours IST (Indian Standard Time), the second one between 19-21 hours IST, and a valley for 14-16 hours IST in all the four seasons considered. Similar peaks are reported in other Indian cities also (Yadav *et al.* [37] at Udaipur; Balakrishnaiah *et al.* [38] at Anantapur; Tiwari *et al.* [39] at Delhi). The morning peak might be associated with increased traffic and the lower Planetary Boundary Layer (PBL) [40]. The late evening peak may be attributed to vehicular traffic emissions and anthropogenic activities. The valley observed in mid-day may be due to the reduced anthropogenic activity and the increase in the PBL height. The late-night reduction in level can be attributed to reduced anthropogenic activities and traffic [41].

The average seasonal level of $PM_{2.5}$ for the BMSCE campus station for the year 2019 is 39±4 μg/m^3, 10±2 μg/m^3, 25±13 μg/m^3, and 45±13 μg/m^3 for the summer, monsoon, post-monsoon and winter season respectively. Similarly, the seasonal PM_{10} levels observed are 96±22 μg/m^3, 39±6 μg/m^3, 61±17 μg/m^3, and 98±24 μg/m^3 for the summer, monsoon, post-monsoon, and winter, respectively. The present observations are compared with those reported by Trivedi *et al.* [27] for the city of Delhi. They report $PM_{2.5}$ levels of 221 μg/m^3, 86 μg/m^3, 58 μg/m^3, and 199 μg/m^3 for winter, summer, monsoon, and post-monsoon respectively. In the case of PM_{10}, their reported levels are 335 μg/m^3, 222 μg/m^3, 89 μg/m^3, and 316 μg/m^3 for winter, summer, monsoon, and post-monsoon respectively. The levels in Delhi for both $PM_{2.5}$ and PM_{10} are higher than the present observations. Delhi is situated in Indo Gangetic Plain (IGP) and is also the second city in India by population. Transportation is attributed as the main cause of higher levels in Delhi by the authors. During the period April 2010 to March 2013, the seasonal variations of $PM_{2.5}$ and PM_{10} for the city of Udaipur, India, were reported by Yadav *et al.* [37]. Their observed levels of $PM_{2.5}$ were 28±9 μg/m^3 and 60±21 μg/m^3 for monsoon and winter seasons, respectively. Similarly, the levels of PM_{10} in winter and monsoon seasons were 131±43 μg/m^3 and 84±39 μg/m^3, respectively. The levels of $PM_{2.5}$ and PM_{10} in Udaipur are higher than the present observations for Bengaluru.

The tropical country of Vietnam has only two distinct seasons, the dry (December-April) and rainy (May–November) seasons. For Ho Chi Minh City (HCMC), Vietnam, Hein *et al.* [33] have observed lower levels of $PM_{2.5}$ in the rainy season, which is due to the washing out of aerosol particles. Higher levels are observed in the dry season. Chaloulakou *et al.* [35] have observed for Aristotelous Street, Athens, Greece, the PM_{10} level to be 77 μg/m^3 in the cold season and 73.9 μg/m^3 in the warm season. The $PM_{2.5}$ level in the cold season is 41 μg/m^3, and in the warm season, 39.7 μg/m^3. Both observations indicate winter-time higher levels. Hoque *et al.* [36] have measured the levels of $PM_{2.5}$ and PM_{10} for the station Darussalam, Mirpur, Dhaka, Bangladesh. The levels of $PM_{2.5}$ and PM_{10} in the dry season (Oct-Feb) are 132 μg/m^3 and 231 μg/m^3, whereas, for the wet season (Mar to Sep), the levels are 47.30μg/m^3 and 89.30 μg/m^3 for $PM_{2.5}$ and PM_{10} respectively.

In general, the PM levels show bimodal distribution on a diurnal scale, with the first peak in the morning and the second one in the late evening. The peaks are attributed to the combined effect of rush hour traffic and the lower PBL. The lower levels in the afternoon

till evening are attributed to reduced anthropogenic activities along with stretching of PBL, resulting in increased dispersion and dilution. The winter time higher levels are due to the inversions that appear during the season. The winds in winter are north-easterly, bringing continental air mass into the city. The lower levels in the monsoon season are attributed to washout by rain. The causation of diurnal and seasonal behavior of $PM_{2.5}$ at Bengaluru is discussed in further detail by Shivkumar *et al.* [16] and Prabhu *et al.* [42].

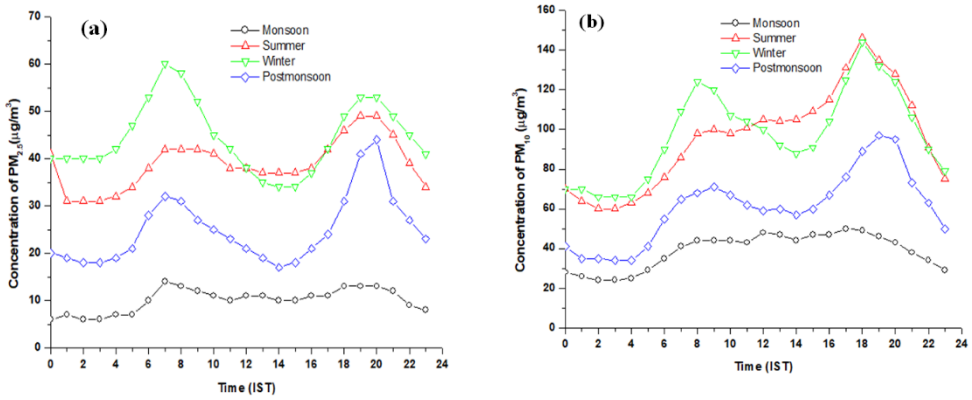

Fig. 2. Season-wise diurnal variability of $PM_{2.5}$and $PM_{10}$for Bengaluru for the year 2019.

5. Time Series, Diurnal and Seasonal Variation of BC

The BC levels measured at the BMSCE campus for the year 2019 are analyzed. Fig. 3a shows the times series variation of BC for the year 2019. As observed for PM factions, the daily average BC levels also show large fluctuations attributed to changing weather conditions. The annual mean level of BC at the BMSCE station is 2.72 µg/m^3, whereas the highest and lowest levels are 6.08 µg/m^3 and 1.46 µg/m^3. Babu *et al.* [43] have reported a BC level of 4.2 µg/m^3 for Bengaluru, which is higher than the present observation. The range of BC mass level reported for the city of Kanpur, India, is 6.0 to 20.0 µg/m^3 [44]. The average levels of BC in different parts of India and around the world are tabulated (Table 2). The present BC level observed for Bengaluru is lower compared to those observed in other cities of India.

The diurnal, seasonal variation of BC at the BMSCE campus is shown in Fig. 3b. As BC is a part of $PM_{2.5}$, it exhibits a similar diurnal pattern. Two peak pattern of BC was also observed in different cities of India (e. g. Yadav *et al.* [37]). The average BC levels observed in the BMSCE station during summer, monsoon, post-monsoon, and winter seasons are 3.13 µg/m^3, 1.99 µg/m^3, 3.07µg/m^{3,} and 3.19 µg/m^{3,} respectively. The BC varies from 2.02 to 4.03 µg/m^3 in winter, 1.97 to 5.05 µg/m^3 in summer, 1.99 to 3.29 µg/m^3 monsoon, and 1.97 to 4.87 µg/m^3 in post-monsoon seasons. The maximum BC concentration is observed in winter, and the minimum is in the monsoon season. The maximum in the winter season may be due to the creation of an inversion layer, which

leads to an increase in the aerosol level. The minimum BC level in monsoon season may be due to washing out by rain. Similar seasonal behavior was observed in the cities of Anantapur and Delhi. Reddy *et al.* [45] have reported 5.05 μg/m^3 in winter, 3.77 μg/m^3 in summer, 1.55 μg/m^3 during monsoon, and 2.33 μg/m^3 in post-monsoon season for the semi-arid city of Anantapur in the year 2012. Tyagi *et al.* [46] have reported season-wise BC levels for Delhi for the year 2016. The levels were 22.76 μg/m^3, 10.30 μg/m^3, 6.05 μg/m^3, and 20.40 μg/m^3 during winter, summer, monsoon, and post-monsoon seasons respectively.

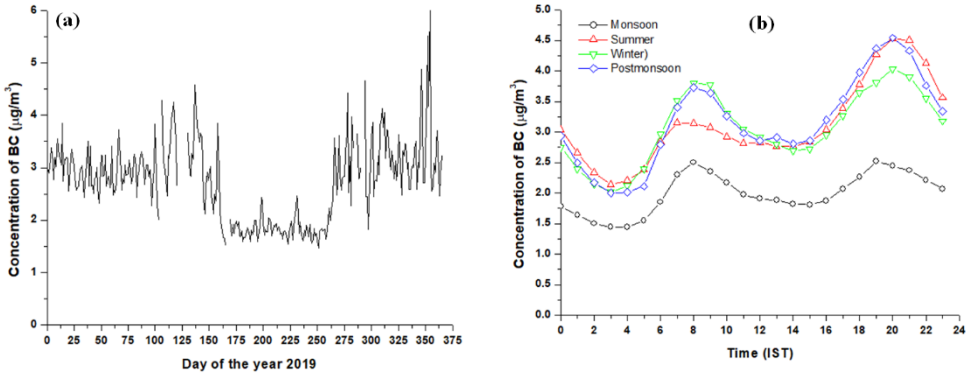

Fig. 3. Time series and season-wise diurnal variability of BC for Bengaluru for the year 2019.

Table 2. Average levels of BC at Bengaluru and different cities of India and the world.

Location	Type of location	Observation period	Mean BC (μg/m^3)	Reference
Bengaluru (BMSCE)	Urban, Continental	Jan to Dec 2019	2.72	Present study
Bengaluru, India	Urban, Continental	Nov 2001	4.2	[43]
Anantapur, India	Semi-arid, Rural	Jan.–Dec. 2010	3.03 ± 0.27	[44]
Nainital, India	High altitude	Dec. 2004	1.36 ± 0.99	[47]
Delhi, India	Urban, Industrialized	Mar.–May. 2006	3–27	[48]
Pune, India	Urban, Industrialized	Jan.–Dec. 2005	4.1	[49]
Ahmedabad, India	Urban, Industrialized	Sep.2003-Jun. 2005	0.21–10.2	[50]
Mumbai, India	Urban, Industrialized	Jan.–Mar. 1999	12.4 ± 5.1	[51]
Hyderabad, India	Urban	Jan. 2004	1.5–11.2	[52]
Kanpur, India	Urban, Continental	Dec. 2004	6–20	[44]
Gadanki, India	Rural	Apr.–Nov. 2008	1–4	[53]
Trivandrum, India	Coastal, Urban	Aug. 2000–Oct. 2001	0.5–8.0	[54]
Nam-Co, Tibet, China	High altitude	Jul. 2006–Jan. 2007	0.82 ± 0.71	[55]
Beijing	Urban	Jul. 1999–Sep. 2000	8.7–10.1	[56]
Guangzhou	Urban	Jul. 2006	4.7	[57]
Xi'an, China	Urban	Sep. 2003–Aug. 2005	14.7 ± 9.5	[58]
Lahore, Pakistan	Costal, Urban	Nov. 2005–Jan. 2006	21.7	[59]
Karachi, Pakistan	Urban	2006–2007	5.9	[60]
Seoul, Korea	Urban	Jun. 1994	4.86–9.86	[61]

6. Spatial Variation of PM at Bengaluru

The daily average levels of both $PM_{2.5}$ and PM_{10} in all six stations are comparable. However, the levels at Bapuji Nagar and Silk Board are slightly higher. This is expected as these stations are located on high-traffic roads. A season-wise and annual comparison of data of PM recorded at all six stations in order to understand the spatial variation in Bengaluru for the year 2019 has been done (Table 3). Season-wise average levels of PM do not show significant spatial variation in Bengaluru. The annual averages at different stations are also comparable. As observed in the case of seasonal, diurnal variation, the PM levels are generally highest during winter and lowest during monsoon. Devaraj *et al.* [62] analyzed the spatial and temporal variations of PM for the period January 2017 to March 2018 for the city of Bengaluru at five sites using CPCB data. Their results also do not indicate significant spatial variation. The nature of the station does not seem to have a greater influence on the levels.

Table 3. Seasonal and annual variation of $PM_{2.5}$ and PM_{10} at different sites of Bengaluru for the year 2019.

Season	BMSCE		Jayanagar		Bapuji Nagar		Hombegowda Nagar		Hebbal		Silk Board	
	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}
Winter	35	84	47	110	47	98	39	88	48	93	41	82
Summer	32	76	38	104	45	95	35	100	38	86	40	91
Post-monsoon	26	49	36	76	37	77	30	63	31	64	27	61
Monsoon	19	44	13	43	26	50	12	75	13	33	21	37
Annual Avg.	28	72	31	78	38	78	27	65	31	67	32	83

7. Role of PBL and VC on PM and BC levels

The Planetary Boundary Layer (PBL) height and Ventilation Coefficient (VC) are the key factors that influence the vertical mixing and dissipation of near-surface pollutants. The effect of PBL and VC on PM levels is analyzed in the present study. The PBL height data has been obtained from MERRA [Modern Era Retrospective-analysis for Research Application]. In general, levels of PM and other trace gases respond to variations in the PBL height. The diurnal variation of PM and trace gases in areas with anthropogenic emissions are interpreted by the daily variation of PBL [63]. The diurnal pattern of the average PBL height over Bengaluru shows a minimum value just before sunrise, increases after sun rises and peaks at mid-day (12-14 h IST), and decreases subsequently. The two peaks observed in the levels of PM and BC on a diurnal scale are related to the reduced PBL height in the morning as well as late evening hours combined with the enhanced human activities (Fig. 4). The lowest level of PM and BC in the mid-day is a consequence of reduced anthropogenic activities and further assisted by the dispersion and dilution caused due to the stretching of the PBL.

The ventilation coefficient (VC) has been calculated by multiplying PBL height with the average wind speed. In addition to the effect of variations in the PBL height on the PM

and BC levels, the surface winds also cause the dispersion and dilution of the pollutants. VC gives the combined effect of PBL and winds on the levels of PM. As can be seen from Fig. 4, higher VC leads to lower levels of PM and BC.

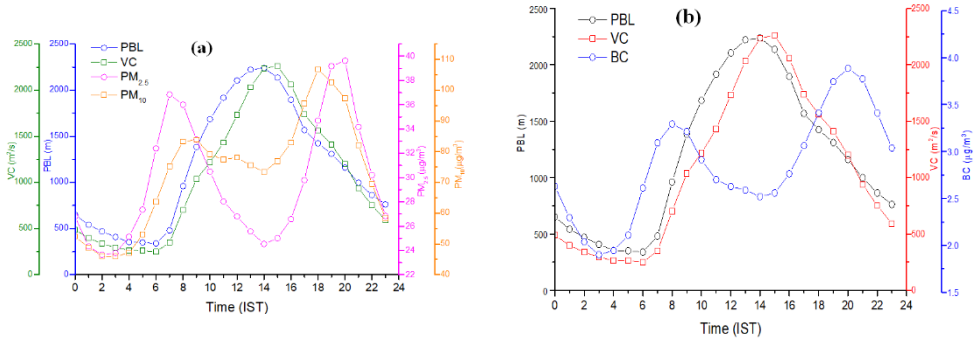

Fig. 4. $PM_{2.5}$, $PM_{10,}$ and BC with PBL height and VC for the year 2019.

8. Role of Meteorological Parameters on PM and BC Levels

Correlation coefficients for PM and BC with meteorological variables - Ambient Temperature (AT), Rainfall (RF), Relative humidity (RH), and Wind Speed (WS) for the year 2019 have been calculated (Fig. 5). $PM_{2.5}$, $PM_{10,}$ and BC are positively correlated with AT and RF with weak correlation coefficients. This indicates the possibility of fresh particle emission being prominent near the observational site. Hence, AT and RF seem to have little role in deciding the aerosol level for the observational year. PM and BC show a moderate negative correlation with RH (except for PM_{10}). The increase in RH may result in hygroscopic growth of the aerosol size leading to increased deposition. The values of correlation coefficients show that hygroscopic growth may be higher in the case of PM_{10} as compared to that among $PM_{2.5}$ and BC. It is known that, in general, BC is non–hygroscopic in nature and also constitutes a part of $PM_{2.5.}$ PM and BC are strongly correlated with negative coefficients with WS. This indicates the dispersion and dilution of PM and BC with an increase in WS.

9. Deepavali Festival

Deepavali, which means 'festival of lights,' is a prominent festival celebrated throughout India. This festival falls in the post-monsoon season, either in October or November month. Bengaluru is an ethnically well-mixed city in India, and hence this festival is celebrated quite extensively. The celebration involves burning of firecrackers for three days, especially at nighttime. In the year 2019, the Deepavali festival was celebrated on the 27^{th}, $28^{th,}$ and 29^{th} of October. The Deepavali PM data archived for five stations (Bapuji Nagar, Hebbal, Hombegowda Nagar, Jayanagar, and Silk Board) and BMSCE campus data are analyzed. The average PM levels three days before and after the festival are used for the comparison. As evident from Figs. 6a and 6b, PM levels during the

festival have increased considerably. The percentage increase in PM during the festival is presented in Table 4. Similar observations during Deepavali from the city of Jabalpur, India, are reported for the year 2012 [64].

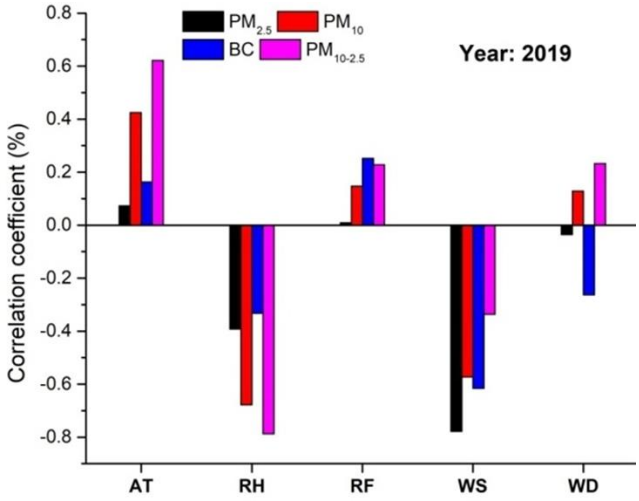

Fig. 5. Correlation of PM and BC with meteorological parameters for the year 2019.

The celebration of the festival by lighting firecrackers is much higher at nighttime than during the day. Hence, data is further analyzed for daytime (6 to 17 IST) and night-time (18 to 6 IST) during the festival days. The values reported in Table 4 clearly show the higher levels during night-time. This clearly shows the burning of crackers is higher during night-time. The levels of PM and BC take four days to a week to reach normal levels after the festival's celebration. Similar observations in the Deepavali festival were found for PM at the site Kankurguchiin the city of Kolkata in November 2010 [65].

In Fig. 6c, BC data of the BMSCE campus during the 2019 Deepavali festival is presented. The levels of BC were found to be marginally higher. Further, BC concentrations are slightly higher at night time during the festival. A similar BC increase for Deepavali in the city of Hyderabad has been reported by Yerramsetti *et al.* [66] using three years (2009-2011) of data.

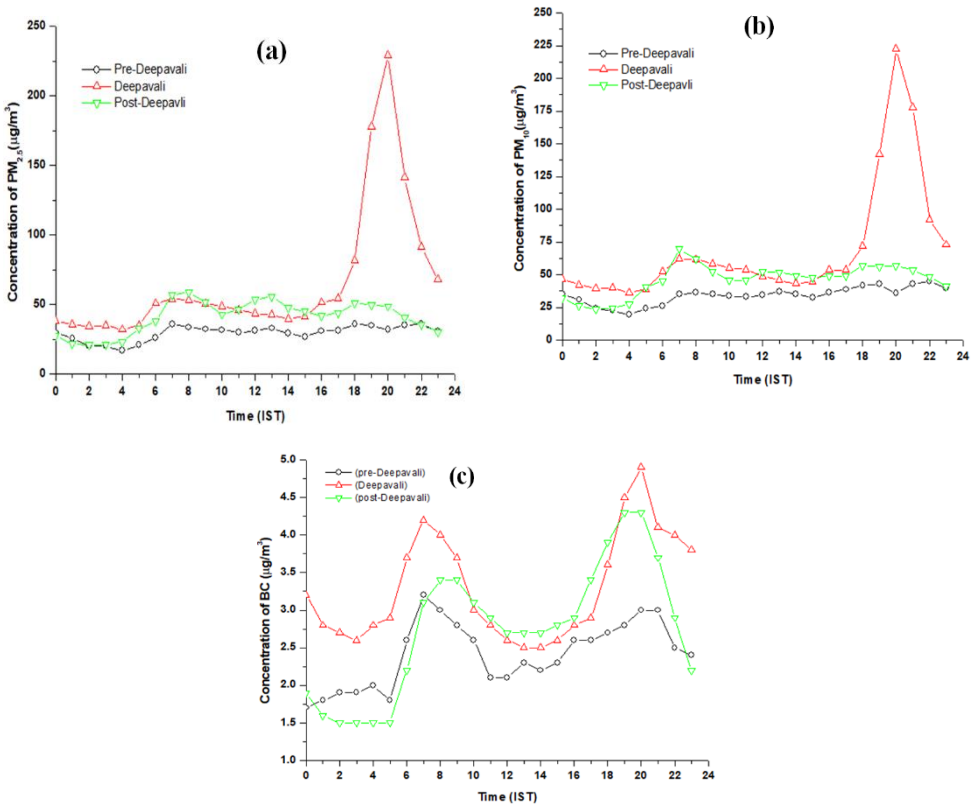

Fig. 6. (a, b), $PM_{2.5}$ and PM_{10} levels during the Deepavali festival in the year 2019, and (c) BC levels during the Deepavali festival in the year 2019 (BMSCE campus).

Table 4. Percentage increase and difference in the night-time (NT) and daytime (DT) of PM during the Deepavali festival for the year 2019.

Stations	Increase in levels of PM (%) during Deepavali		Differences between NT and DT	
	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}
BMSCE	350	214	128	32
Jayanagar	278	173	50	9
Bapuji Nagar	183	160	73	23
Hebbal	293	194	90	47
Hombegowda Nagar	267	313	50	54
Silk Board	200	119	62	26

10. Health Risk Assessment

PM particles have a direct connection to health conditions that can be fatal. WHO created the AIRQ+ model to estimate the effects of air pollution exposure on health [67]. The health effects of ambient air pollutants, including $PM_{2.5}$, NO_2, O_3, and BC, can be estimated using this software. The disease-specific baseline mortality rate for the state of

Karnataka (for 2019) was taken from the global burden disease (GBD) for India [68]. The Air Q+ program's default relative risk (RR) values for each health endpoint were applied in this study. PM is linked to early human mortality, which results in adult health conditions like ischemic heart disease (IHD), chronic obstructive pulmonary disease (COPD), cerebrovascular disease (CEV, stroke), lung cancer (LC), and acute lower respiratory illness (ALRI) in kids less than five years of age. For the entire of India in the year 2011, Ghude *et al.* [69] conducted an investigation of the impact of PM on IHD, stroke, COPD, LC, and ALRI. The present estimation follows their procedure. The premature deaths attributable to PM in Bengaluru, India, for the year 2019 are displayed in Table 5. Per 1 million residents, IHD is the most common adult health issue in Bengaluru, followed by COPD due to exposure to PM.

Table 5. Premature mortality per million populations for the city of Bengaluru for the year 2019 due to exposure to PM.

Sl. No	Health endpoints	Premature mortalities
1	Ischemic heart disease	35913 (29611-42973)
2	Stroke	15182 (12286-18422)
3	Chronic obstructive pulmonary disease	23574 (18163-28734)
4	Tracheal, Bronchus, and Lung Cancer	1783 (1391-2293)
5	Acute lower respiratory illness	3886 (2799-5242)

11. Conclusion

The average levels of PM measured at six stations in the tropical megacity of Bengaluru, India, during the year 2019 show large fluctuations on a daily basis. The 24 h average mass levels of $PM_{2.5}$ were less compared to the INAAQS threshold of 40 $\mu g/m^3$, and levels of PM_{10} exceeded the INAAQS threshold of 60 $\mu g/m^3$ for the year. The diurnal variations of $PM_{2.5,}$ $PM_{10,}$ and BC mass levels show two distinct peaks which coincide with rush hour traffic. A significant seasonality is revealed in the measured mass levels of $PM_{2.5,}$ $PM_{10,}$ and BC, with the highest occurring for winter and the lowest in the wet period of monsoon. A weak positive correlation between PM and BC with AT and RF indicates the possibility of fresh particle emission. A moderate correlation observed with RH shows the possibility of the hygroscopic growth of the particles. A strong negative correlation with WS indicates the dispersion and dilution of the particles with increasing WS. During the Deepavali festival period for the year 2019, the levels of PM and BC are observed to be higher as compared to before and after the festival. The night-time levels are found to be higher than the daytime ones during the festival. The analysis of the death rates for IHD, COPD, stroke, lung cancer, and ALRI in children shows that IHD has the highest PM exposure risk.

Acknowledgments

The Ministry of Earth Sciences (MoES) of the Indian government funds the Indian Institute of Tropical Meteorology (IITM) in Pune. For the mutual benefit of their research,

the authors sincerely express their gratitude to G. Krishnan, Director, IITM, and MoES, for the MAPAN air quality station at BMS College of Engineering, Bengaluru. The author's viewpoints and findings in this study might not align with those of the companies they work for. The authors also acknowledge the Central Pollution Control Board (Government of India). The BMS College of Engineering's authors thank S. Muralidhara, the Principal, for his encouragement.

References

1. M. X. Wang, R. J. Zhang, and Y. F. Pu, Adv. Atmos. Sci. **18**, 576 (2001). https://doi.org/10.1007/s00376-001-0046-9
2. R. Zhang, M. Wang, X. Zhang, and G. Zhu, Powder Technology, **137**. 77 (2003). https://doi.org/10.1016/j.powtec.2003.08.056
3. A. Ianniello, F. Spataro, G. Esposito, I. Allegrini, M. Hu, and T. Zhu, Atmos. Chem. Phys. **11**, 10803 (2011). https://doi.org/10.5194/acp-11-10803-2011
4. J. Schwartz, F. Laden, A. Zanobetti, and D.W. Dockery, In Epidemiology **12**, 64 (2001). https://doi.org/10.1097/00001648-200101000-00010
5. L. H. Chen, S. F. Knutsen, L. Beeson, M. Ghamsary, D. Shavlik, F. Petersen, and D. Abbey, Annals of Epidemi. **15**, 642 (2005). https://doi.org/10.1016/j.annepidem.2005.06.035
6. F. Dominici, A. McDermott, M. Daniels, S. L. Zeger, and J. M. Samet, J. Toxicol. Environ. Heal. **68**, 1071 (2005). https://doi.org/10.1080/15287390590935932
7. Í. S. Santiago, T. F. Silva, E. V. Marques, F. M. D. S. Barreto, A. G. Ferreira, C. A. Rocha, K. V. Mendonça, and R. M. Cavalcante, Environ. Sci. Poll. Res. **28**, 42670 (2021). https://doi.org/10.1007/s11356-021-13590-6
8. V. Ramanathan and G. Carmichael. Nat. Geo. **1**, 221 (2008). https://doi.org/10.1038/ngeo156
9. M. Z. Jacobson, Nature, **409**, 695 (2001). https://doi.org/10.1038/35055518
10. A. A. Koelmans, M. T. Jonker, G. Cornelissen, T. D. Bucheli, P. C. V. Noort, and Ö. Gustafsson, Chemosphere **63**, 365 (2006). https://doi.org/10.1016/j.chemosphere.2005.08.034
11. J. E. Penner, H. Eddleman, and T. Novakov, Atmos. Environ. Part A Gen. Topics **27**, 1277 (1993). https://doi.org/10.1016/0960-1686(93)90255-W
12. W. F. Cooke and J. J. Wilson, J. Geophy. Res. Atmos. **101**, 19395 (1996). https://doi.org/10.1029/96JD00671
13. L. Husain, V. A. Dutkiewicz, A. J. Khan, and B. M. Ghauri, Atmos. Environ. **41**, 6872 (2007). https://doi.org/10.1016/j.atmosenv.2007.04.037
14. C. Liousse, J. E. Penner, C. Chuang, J. J. Walton, H. Eddleman, and H. Cachier, J. Geophys. Res. Atmos. **101**, 19411 (1996). https://doi.org/10.1029/95JD03426
15. TERI. Final Report on Urban Planning Characteristics to Mitigate Climate Change in Context of Urban Heat Island Effect Bangalore, The Energy and Resources Institute [Project Report No. 2016BG03] 82 (2017).
16. M. Shivkumar, G. Dhanya, K. E. Ganesh, T. S. Pranesha, K. R. Sudhindra, D. Chate, and G. Beig, Environ. Monitoring Assess. **194**, 1 (2022). https://doi.org/10.1007/s10661-022-10235-0
17. G. Dhanya, T. S. Pranesha, K. Nagaraja, D. M. Chate, and G. Beig, J. Sci. Res. **14**, 459 (2022). https://doi.org/10.3329/jsr.v14i2.55626
18. D. Gopi, T. S. R. Pranesha, D. M. Chate, and G. Beig, Photochem Photobiol. **98**, 1312 (2022). https://doi.org/10.1111/php.13626
19. R. Sindhwani and P. Goyal. Atmos. Poll. Res. **5**, 438 (2014). https://doi.org/10.5094/APR.2014.051
20. G. Li, C. Fang, S. Wang, and S. Sun, Environ. Sci. Tech. **50**, 11452 (2016). https://doi.org/10.1021/acs.est.6b02562
21. B. Ambade, Urban Climate. **26**, 149 (2018). https://doi.org/10.1016/j.uclim.2018.08.009

22. M. Sateesh, V. K. Soni, and P. V. S. Raju, Earth Systems Environ. **2**, 293 (2018). https://doi.org/10.1007/s41748-018-0054-x
23. U. C. Kulshrestha, T. N. Rao, S. Azhaguvel, and M. J. Kulshrestha, Atmos. Environ. **38**, 4421 (2004). https://doi.org/10.1016/j.atmosenv.2004.05.044
24. R. Garaga and S. H. Kota, J. Health Poll. **8**, (2018). https://doi.org/10.5696/2156-9614-8.20.181206
25. M. Yunesian, R. Rostami, A. Zarei, M. Fazlzadeh, and H. Janjani, Microchem. J. **150**, 104174 (2019). https://doi.org/10.1016/j.microc.2019.104174
26. A. D. A. Hansen, Berkeley, California, USA, Magee Scientific (2005).
27. D. K. Trivedi, K. Ali, and G. Beig, Sci. Total Environ. **478**, 175 (2014). https://doi.org/10.1016/j.scitotenv.2014.01.101
28. N. K. Oanh, N. Upadhyay, Y. H. Zhuang, Z. P. Hao, D. V. S. Murthy, P. Lestari, J. T. Villarin, K. Chengchua, H. X. Co, N. T. Dung, and E. S. Lindgren, Atmos. Enivron. **40**, 3367 (2006). https://doi.org/10.1016/j.atmosenv.2006.01.050
29. A. S. Pipal, A. Kulshrestha, and A. Taneja, Atmos. Environ. **45**, 3621 (2011). https://doi.org/10.1016/j.atmosenv.2011.03.062
30. S. Tiwari, A. K. Srivastava, D. S. Bisht, T. Bano, S. Singh, S. Behura, M. K. Srivastava, D. M. Chate, and B. Padmanabhamurty, J. Atmos. Chem. **62**, 193 (2009). https://doi.org/10.1007/s10874-010-9148-z
31. F. D. Pope, M. Gatari, D. Ng'ang'a, A. Poynter, and R. Blake, Atmos. Chem. Phys. **18**, ID 15403 (2018). https://doi.org/10.5194/acp-18-15403-2018
32. C. M. Salvador, A. D. Alindajao, K. B. Burdeos, M. A. Lavapiez, J. R. Yee, A. T. B. VII, P. C. B. Pabroa, and R. Y. Capangpangan, Aerosol Air Qual. Res. **22**, 210269 (2022). https://doi.org/10.4209/aaqr.210269
33. T. T. Hien, N. D. T. Chi, N. T. Nguyen, N. Takenaka, and D. H. Huy, Aerosol and Air Qual. Res. **19**, 2239 (2019). https://doi.org/10.4209/aaqr.2018.12.0471
34. K. Vellingiri, K. H. Kim, C. J. Ma, C. H. Kang, J. H. Lee, I. S. Kim, and R. J. Brown, Chemosphere **119**, 812 (2015). https://doi.org/10.1016/j.chemosphere.2014.08.049
35. A. Chaloulakou, P. Kassomenos, N. Spyrellis, P. Demokritou, and P. Koutrakis, Atmos. Environ. **37**, 649 (2003). https://doi.org/10.1016/S1352-2310(02)00898-1
36. M. M. Hoque, Z. Ashraf, H. Kabir, E. Sarker, and S. Nasrin, Atmos. J. Pure Appl. Biosci. **15** (2020). https://doi.org/10.34104/ajpab.020.15023
37. R. Yadav, L. K. Sahu, S. N. A. Jaaffrey, and G. Aero. Air. Qual. Res. Beig, Aerosol Air Qual. Res. **14**, 1613 (2014). https://doi.org/10.4209/aaqr.2013.10.0310
38. G. Balakrishnaiah, K. R. Kumar, B. Reddy, K. R. Gopal, R. R. Reddy, L. S. S. Reddy, K. Narasimhulu, Y. N. Ahammed, C. Balanarayana, K. K. Moorthy, and S. S. Babu, Ind. J. Radio Space Phys. **40**, 95 (2011).
39. S. Tiwari, A. K. Srivastava, D. S. Bisht, P. Parmita, M. K. Srivastava, and S. D. Attri, Atmos. Res. **125**, 50 (2013). https://doi.org/10.1016/j.atmosres.2013.01.011
40. R. B. Stull. An Introduction to Boundary Layer Meteorology, (Springer Science & Business Media, 1988) Vol. **13**. https://doi.org/10.1007/978-94-009-3027-8
41. R. Saini, G. S. Satsangi, and A. Taneja, Indian J. Radio Space Phys. **37**, 121 (2008).
42. V. Prabhu, P. Singh, P. Kulkarni, and V. Sreekanth, Environ. Moni. Assess. **194**, (2022). https://doi.org/10.1007/s10661-022-09852-6
43. S. S. Babu, S. K. Satheesh, and K. K. Moorthy, Geophys. Res. Lett. **29**, 27 (2002). https://doi.org/10.1029/2002GL015826
44. S. N. Tripathi, S. Dey, V. Tare, and S. K. Satheesh, Geophys. Res. Lett. **32**, (2005). https://doi.org/10.1029/2005GL022515
45. B. S. K. Reddy, K. R. Kumar, G. Balakrishnaiah, K. R. Gopal, R. R. Reddy, L. S. S. Reddy, Y. N. Ahammed, K. Narasimhulu, K.K. Moorthy, and S. S. Babu, Aerosol Air Qual. Res. 344 (2012). https://doi.org/10.4209/aaqr.2011.10.0159
46. C. Tyagi, N. C. Gupta, V. K. Soni, and K. Sarma, Environ. Claims J. **32**, 101 (2020). https://doi.org/10.1080/10406026.2019.1699723

47. P. A. Pant, P. Hegde, U. C. Dumka, R. Sagar, S. K. Satheesh, K. K. Moorthy, A. Saha, and M. K. Srivastava, J. Geophys. Res. Atmos. 111 (2006). https://doi.org/10.1029/2005JD006768
48. S. N. Beegum, K. K. Moorthy, S. S. Babu, S. K. Satheesh, V. Vinoj, K. V. S. Badarinath, P. D. Safai, P. C. S. Devara, S. Singh, U. C. Dumka, and P. Pant, Atmos. Environ. **43**, 1071 (2009). https://doi.org/10.1016/j.atmosenv.2008.11.042
49. P. D. Safai, S. Kewat, P. S. Praveen, P. S. P. Rao, G. A. Momin, K. Ali, and P. C. S. Devara, Atmos. Environ. **41**, 2699 (2007). https://doi.org/10.1016/j.atmosenv.2006.11.044
50. S. Ramachandran and T. A. Rajesh. J. Geophys. Res. Atmos. **112**, D06211 (2007). https://doi.org/10.1029/2006JD007488
51. C. Venkataraman, C. K. Reddy, S. Josson, and M. S. Reddy, Atmos. Environ. **36**, 1979 (2002). https://doi.org/10.1016/S1352-2310(02)00167-X
52. K. Madhavi Latha, K. V. S. Badrinath, and K. K. Moorthy, Curr. Sci. **86**, 451 (2004).
53. H. Gadhavi and A. Jayaraman. In Annales Geophysicae **28**, 103 (2010). https://doi.org/10.5194/angeo-28-103-2010
54. S. S. Babu, and K. K. Moorthy. Geophy. Res. Lett. **29**, 13 (2002). https://doi.org/10.1029/2002GL015662
55. J. Ming, C. Xiao, J. Sun, S. Kang, and P. Bonasoni, J. Environ. Sci. **22**, 1748 (2010). https://doi.org/10.1016/S1001-0742(09)60315-6
56. K. He, F. Yang, Y. Ma, Q. Zhang, X. Yao, C.K. Chan, S. Cadle, T. Chan, and P. Mulawa, Atmos. Environ. **35**, 4959 (2001). https://doi.org/10.1016/S1352-2310(01)00301-6
57. R. L. Verma, L. K. Sahu, Y. Kondo, N. Takegawa, S. Han, J. S. Jung, Y. J. Kim, S. Fan, N. Sugimoto, M. H. Shammaa, and Y. H. Zhang, Atmos. Chem. Phys. **10**, 6471 (2010). https://doi.org/10.5194/acp-10-6471-2010
58. J. J. Cao, C. S. Zhu, J. C. Chow, J. G. Watson, Y. M. Han, G. H. Wang, Z. X. Shen, and Z. S. An, Atmos. Res. **94**, 194 (2009). https://doi.org/10.1016/j.atmosres.2009.05.009
59. L. Husain, V. A. Dutkiewics, A. J. Khan, and B. M. Ghauri, Atmos. Environ. **41**, 6872 (2007). https://doi.org/10.1016/j.atmosenv.2007.04.037
60. V. A. Dutkiewicz, S. Alvi, B. M. Ghauri, M. I. Choudhary, and L. Husain, Atmos. Environ. **43**, 1737 (2009). https://doi.org/10.1016/j.atmosenv.2008.12.043
61. Y. P. Kim, K. C. Moon, J. H. Lee, and N. J. Baik, Atmos. Environ. **33**, 2751 (1999). https://doi.org/10.1016/S1352-2310(98)00313-6
62. S. Devaraj, S. Tiwari, H. K. Ramaraju, U. C. Dumka, M. Sateesh, P. Parmita, and G. P. Shivashankara, Arch. Environ. Contaminat. Toxicol. **77**, 214 (2019). https://doi.org/10.1007/s00244-019-00643-8
63. L. Kaser, T. Karl, B. Yuan, R. L. Mauldin III, C. A. Cantrell, A. B. Guenther, E. G. Patton, A. J. Weinheimer, C. Knote, J. Orlando, and L. Emmons, Geophys. Res. Lett. **42**, 10 (2015). https://doi.org/10.1002/2015GL066641
64. R. K. Srivastava, K. Sagar, and G. Beig, Int. J. Environ. Sci. Toxicology, **136**, 2408 (2014).
65. A. Chatterjee, C. Sarkar, A. Adak, U. Mukherjee, S. K. Ghosh, and S. Raha, Aerosol Air Qual. Res. **13**, 1133 (2013). https://doi.org/10.4209/aaqr.2012.03.0062
66. V. S. Yerramsetti, A. R. Sharma, N. G. Navlur, V. Rapolu, N. S. K. Dhulipala, and P. R. Sinha, Environ. Moni. Assess. **185**, 7309 (2013). https://doi.org/10.1007/s10661-013-3102-x
67. WHO, AirQ+ software tool for health risk assessment of air pollution (2021). https://www.who.int/europe/tools-and-toolkits/airq---software-tool-for-health-risk-assessment-of-air-pollution
68. Indian Council of Medical Research (ICMR)., Public Health Foundation of India (PHFI), & Institute for Health Metrics and Evaluation (IHME), GBD India compare data visualization (New Delhi: ICMR, PHFI, and IHME, 2019).
69. S. D. Ghude, D. M. Chate, C. Jena, G. Beig, R. Kumar, M. C. Barth, G. G. Pfister, S. Fadnavis, and P. Pithani, Geophys. Res. Lett. **43**, 4650 (2016). https://doi.org/10.1002/2016GL068949