



The association between particulate matter concentration and meteorological parameters in Dhaka, Bangladesh

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Abstract

Detrended cross-correlation and multiple regression analyses were applied to a 5 year dataset (2013–2017) of concentration of particulate matter with aerodynamic diameters less than 2.5 ($PM_{2.5}$) and 10 μm (PM_{10}), and a set of meteorological parameters (rainfall, wind speed, temperature, solar radiation and relative humidity) to determine seasonal dependence of PM in Dhaka, Bangladesh. PM was negatively correlated with all meteorological parameters except for solar radiation. The response of PM to wind speed, relative humidity and rainfall had no lag, whereas a 1 day lagged response of PM was observed with temperature and solar radiation. Seasonal cross-correlation analysis suggests dispersion of PM by strong wind during pre-monsoon and monsoon seasons, while the increase of PM concentration occurs from local pollution sources during the less windy winter. The effect of relative humidity on the deposition of PM (especially the coarser fraction) is more pronounced than the effect of rainfall during pre-monsoon. The outcome of multiple regression analysis was consistent with the univariate analysis and showed that meteorological parameters could explain up to 76% and 73% of daily $PM_{2.5}$ and PM_{10} variation, respectively. The association of PM with meteorological parameters in Dhaka city is similar to other countries located in subtropical climate regions. Our results serve as a reference for future studies to predict PM concentration through meteorological variation to facilitate air pollution management in Dhaka city.

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1 Introduction

Deterioration of air quality in urban environments around the world has occurred with high economic growth, rapid industrial development and increased emissions from motor vehicles (Hien et al. 2002; Zhao et al. 2009). Like other countries, Bangladesh has been experiencing severe air pollution, particularly during winter, when particles with an aerodynamic diameter less than 2.5 ($PM_{2.5}$) and 10 μm (PM_{10}) in ambient air exceed up to 4 and 2.5 times the national standards, respectively (Islam et al. 2015; Rouf et al. 2011). Anthropogenic activities are the primary sources of urban particulate matter (PM), which has become a significant threat to public health in the capital city of Dhaka (Rouf et al. 2011; Begum et al. 2014). Throughout the winter season, Dhaka remains one of the worst polluted cities globally in terms of air quality (WHO 2016). Here, $PM_{2.5}$ contributes to 30–50% of PM_{10} , and improvement of the overall air quality hinges on proper control of both PM size fractions (Begum et al. 2013).

Exposure to ambient PM can cause adverse health effects. Studies confirmed that particulate and acid aerosols in the air are highly correlated with chronic respiratory illness,

lung cancer, bronchial diseases, and adverse cardiovascular effects leading to premature death (Dockery et al. 1993; Pope et al. 2002; Stieb et al. 2002). The increased concentration of thoracic coarse particles PM_{10} and fine particles $PM_{2.5}$ are found to be associated with an increased heart attack (Dockery et al. 1993; Pope et al. 2002). Besides, high PM_{10} concentration in the air reduces visibility during driving and causes localized warming (Ramanathan et al. 2001; Dayan and Levy 2005).

Meteorology is a significant factor in the temporal variation of PM concentrations. The accumulation of PM, its removal efficiency and its chemical formation largely depend on wind speed and direction, temperature, rainfall rate, solar radiation, and relative humidity (Asimakopoulos et al. 2012; Trivedi et al. 2014; Islam et al. 2015; Afrin et al. 2021). A study of 20 air quality monitoring stations within New York City showed that wind direction and speed, temperature and relative humidity were the most influential parameters to control $PM_{2.5}$ in the ambient air (DeGaetano and Doherty 2004). Analyzing an 11 year dataset in the USA, another study showed that temperature, relative humidity, precipitation and stagnant days significantly influence $PM_{2.5}$ variation (Tai et al. 2010). A study in Beijing showed that the condensation factor, a function of temperature and relative humidity, influences $PM_{2.5}$ concentration (Wang et al. 2013). PM_{10} concentration in Germany appeared to be affected by both meteorological and local traffic conditions, but it was suggested that meteorological parameters had a larger influence than the other. (Gietl and Klemm 2009). Similar observations were made by Munir et al. (2013) in Makkah, where temperature and wind speed were significant contributors to PM_{10} variation.

In Bangladesh, the abundance, composition and sources of PM in urban environments are widely studied (Rouf et al. 2011; Begum et al. 2014; Islam et al. 2015). In Dhaka city, brick kilns, motor vehicles, fugitive lead, road dust, soil dust and sea salt are primarily responsible for the high concentration of $PM_{2.5}$ and PM_{10} in ambient air (Begum et al. 2014). Seasonal variation and transboundary impacts on $PM_{2.5}$ and PM_{10} were also investigated (Begum et al. 2016). Using Pearson correlation, Islam et al. (2015) showed that meteorological parameters might influence PM concentration in Dhaka city, though the extent to which these parameters can influence air quality remains poorly understood. PM concentration in Dhaka city has distinct seasonal patterns. Therefore, time-series analysis tools can be more suitable for analyzing trends and seasonal influences. Seasonal cross-correlation analysis has previously been applied to determine the association of environmental variables to disease outbreaks in Bangladesh (Akanda et al. 2011). In this study, we investigated the associations between PM and meteorological parameters on annual and seasonal scales using cross-correlation of the corresponding time-series data.

Furthermore, we performed a multiple regression analysis to determine the relative contribution of meteorological parameters on ambient concentrations of $PM_{2.5}$ and PM_{10} . The PM ($PM_{2.5}$ and PM_{10}) and meteorological data for 2013–2017 from a Continuous Air Monitoring Station (CAMS) in Dhaka city was used. The objective is to understand the correlation between particulate matter concentration and meteorological parameters at seasonal and annual scales and determine how much PM variability can be attributed to meteorological parameters in a highly dense urban area.

2 Site description and input data characteristics

There are 11 Continuous Air Monitoring Stations (CAMS) throughout Bangladesh (manufacturer: Met One Instruments, Inc., USA), operated by the Department of Environment (DoE). Hourly air quality and meteorological parameter monitoring are done in the CAMS. The monitors are calibrated every week employing reference gauges. A 5 year dataset (2013–2017) of $PM_{2.5}$ and PM_{10} concentrations and meteorological parameters (wind speed, ambient temperature, relative humidity, rainfall, and solar radiation) of CAMS-3 (Darus Salam Station, Mirpur, Dhaka) (Fig. 1) was collected from the DoE. The Darus Salam Station location, situated 100 m from the main road, represents a typical urban area in Bangladesh characterized by heavy traffic and crowded business areas. We used daily values (24 h average) of all parameters computed from the hourly data for this analysis. The raw dataset from DoE contained outliers and missing data, which may be due to instrumentation or acquisition error. For addressing the issue of missing values, we used either of the two methods: (1) linear interpolation to determine surrogate values for the missing data if the duration of missing data was small (i.e., 1–3 days), (2) k -nearest neighbour (k -NN) algorithm, if the missing data are for extended periods (more than 3 days). For the latter case, missing data were inferred by adjusting the value of k using a trial and error method through an iterative process to minimize residual error. An iterative process was also applied to eliminate the outliers. The detailed processes are described in Supplementary Materials.

Figure 2 shows the PM profiles during 2013–2017, which show distinct seasonal patterns. The highest and lowest concentrations of both PM fractions ($PM_{2.5}$ and PM_{10}) occur during the month of December–February (winter season) and July–September (rainy season), respectively. During the study period (2013–2017), the highest daily $PM_{2.5}$ concentration was observed during January 2013 ($227.4 \mu\text{g}/\text{m}^3$), whereas the lowest was observed during July 2016 ($19.2 \mu\text{g}/\text{m}^3$). Likewise, a maximum PM_{10} daily average concentration

Fig. 1 Location of CAMS-3 and the position of brick kilns in and around Dhaka city

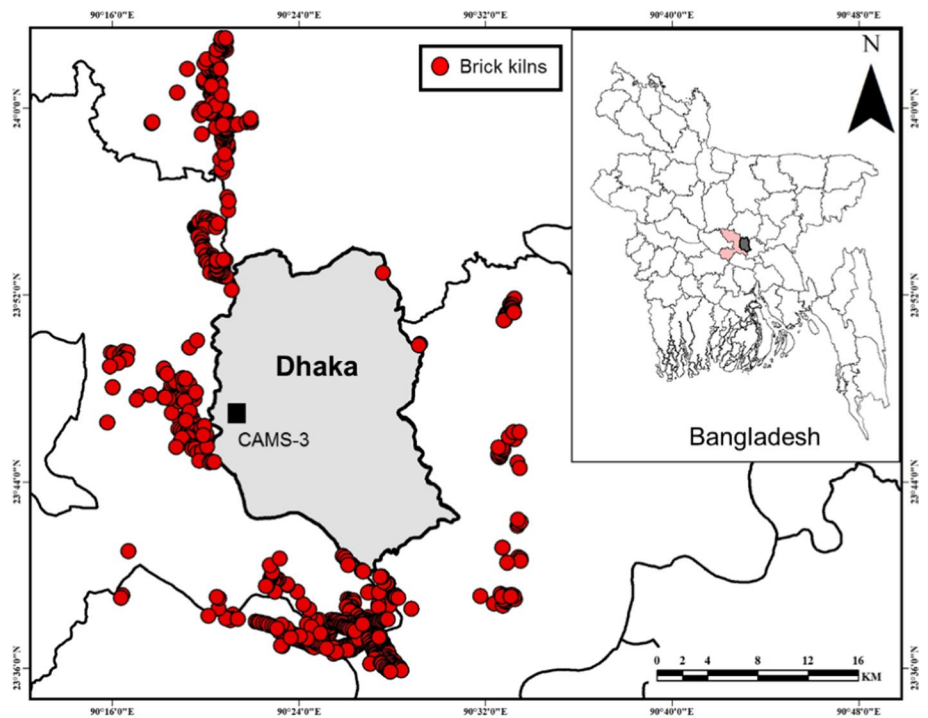
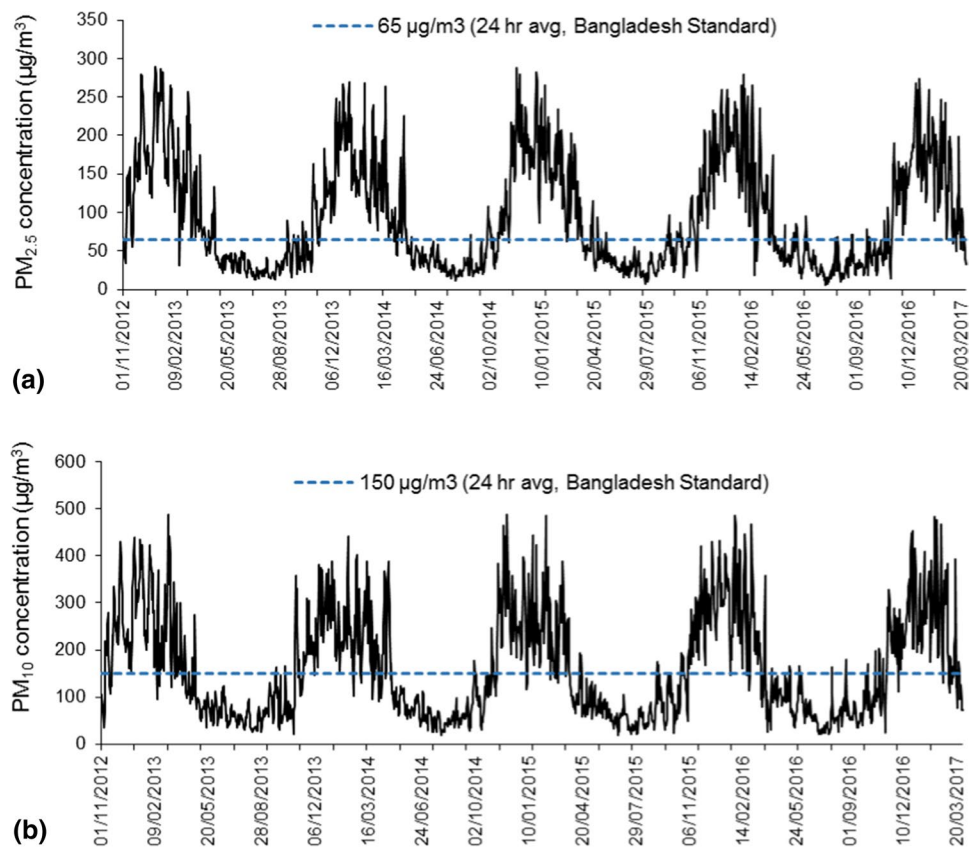


Fig. 2 a The 24 h average $PM_{2.5}$ and **b** PM_{10} concentration with corresponding Bangladesh National Ambient Air Quality Standard (BNAAQs)



of $335 \mu\text{g}/\text{m}^3$ was found in January 2016, whereas the minimum value of $46.7 \mu\text{g}/\text{m}^3$ was found in July 2014. The blue dashed horizontal lines represent the Bangladesh National

Ambient Air Quality Standards for daily $PM_{2.5}$ ($65 \mu\text{g}/\text{m}^3$) and PM_{10} ($150 \mu\text{g}/\text{m}^3$). Daily PM concentration frequently exceeds the standard during December–February (98.7%

exceedance for PM_{2.5} and 96.2% exceedance for PM₁₀), whereas they remain within the standard for July–September.

Table 1 shows a season-wise account of the input meteorological data during 2013–2017. In Bangladesh, a year is broadly divided into four different seasons: winter (December–February), pre-monsoon (March–May), monsoon (June–September) and post-monsoon (October–November) (Begum et al. 2014). The climate of Bangladesh experiences distinct weather variations during different seasons. The winter season is characterized by cold and dry air, low temperature, reduced solar radiation, low wind speed, scattered rainfall, and low relative humidity. During pre-monsoon, rainfall is moderately high with a significant increase in relative humidity compared to winter; wind speed remains at its maximum, and atmospheric temperature and solar radiation increase during this season. During monsoon, along with high wind speed, relative humidity and temperature, the rainfall remains at its highest. In the post-monsoon, precipitation, relative humidity, temperature, solar radiation and wind speed decrease.

3 Methodology

3.1 Correlation analysis

We performed a cross-correlation analysis to determine the association and time dependency between PM concentration and meteorological parameters. The original time-series may be autocorrelated, resulting in spurious cross-correlation over a wide range of lag periods. Kalman filter, a whitening filter based on the recursion algorithm, is applied to the original time-series to overcome this situation. We used the formulation of Harvey (1990) and Aiube (2005) to implement the Kalman filter algorithm. The process of treating the data is discussed in detail in the Supplementary Materials.

The basic cross-correlation formulas we used are as follows:

Table 1 Average values of meteorological parameters in Dhaka city for the four seasons during the period 2013–2017

Season	Meteorological parameters				
	WS (ms ⁻¹)	T (°C)	RH (%)	SR (Wm ⁻² d ⁻¹)	R (cmd ⁻¹)
Winter	1.62	20.56	68.09	144.45	0.06
Pre-monsoon	2.73	28.47	65.17	220.56	0.14
Monsoon	2.58	27.32	76.96	181.03	0.26
Post-monsoon	1.35	26.55	68.84	173.24	0.08

WS wind speed, T temperature, RH relative humidity, SR solar radiation, R rainfall

$$\text{when } k \geq 0, C_{xy}(k) = \sum_{t=1}^{T-k} \frac{1}{T} [x(t) - \bar{x}] [y(t+k) - \bar{y}] \quad (1)$$

$$\text{when } k \leq 0, C_{xy}(k) = \sum_{t=1}^{T-k} \frac{1}{T} [y(t) - \bar{y}] [x(t-k) - \bar{x}] \quad (2)$$

where, $C_{xy}(k)$ is cross-correlation function, $x(t)$ is the respective meteorological parameter at time t , $y(t+k)$ is the concentration of PM at time $t+k$, k is the lag between the two time-series x and y , and T is the total number of elements in series x and y .

To standardize the correlation values, we calculated the cross-correlation coefficient, which is given by

$$r_{xy}(k) = \frac{C_{xy}(k)}{S_x S_y} \quad (3)$$

where $S_x = \sqrt{C_{xx}(0)}$ and $S_y = \sqrt{C_{yy}(0)}$.

If $r_{xy} > 0$, the two series are positively correlated. If $r_{xy} < 0$, they are negatively correlated. According to the formula, when $k > 0$, x leads y by k time units and when $k < 0$, y leads x by k time units.

3.2 Multiple regression analysis

We used multiple regression analysis to evaluate how much of the variability in PM can be explained by the meteorological parameters. We utilized a forward variable selection criterion based on the coefficient of determination (r^2) values of each meteorological parameter (significance level, $p < 0.01$) and incrementally added the variables which have higher correlation coefficients. The underlying assumptions of using multiple regression analysis were verified, explained in the Supplementary Materials.

The regression equation is in the form of

$$y = \beta_0 + \sum_{k=1}^n \beta_k x_k + \varepsilon \quad (4)$$

where n is the number of meteorological parameters ($n = 1 \sim 5$), y is the concentration of PM_{2.5} or PM₁₀, x denotes the meteorological parameters (wind speed, temperature, rainfall, relative humidity and solar radiation), β is the regression coefficient, and ε is the error term [where $\varepsilon = (y_i - \hat{y})$, y_i = observed y values and \hat{y} = y values given by the Eq. (4)].

The coefficient of determination (r^2) is defined as

$$r^2 = \frac{St - Sr}{St} \quad (5)$$

where, St and Sr represent the total sum of squares ($\sum_{i=1}^n (y_i - \bar{y})^2$) and error sum of squares ($\sum_{i=1}^n (y_i - \hat{y})^2$), respectively.

The coefficient of determination (r^2) continues to increase with increasing terms to the model, leading to overfitting of the model. Hence, adjusted r^2 is introduced, which modifies the r^2 based on the added terms to the model:

$$\text{Adjusted } r^2 = 1 - (1 - r^2) \frac{m - 1}{m - n - 1} \quad (6)$$

where, m is the number of elements in a series, and n is the number of independent variables.

To assess the predictive ability of the model, we used the Prediction Error Sum of Squares (PRESS) as an indicator. The smaller the PRESS value, the better the predictive ability of the model. PRESS is defined as follows:

$$\text{PRESS} = \sum_i^T \frac{(y_i - \hat{y})^2}{(1 - h_{ii})^2} \quad (7)$$

where, h_{ii} is defined as the i^{th} 'Leverage Value,' which only depends on the independent variable x . PRESS value is more effective than adjusted r^2 to assess the predictability and check excess independent variables. For $n=2$ and sample size of T ,

$$h_{ii} = \frac{1}{T} + \frac{(x_i - \bar{x})^2}{\sum_{j=1}^n (x_j - \bar{x})^2} \quad (8)$$

A significance level of 1% ($p=0.01$) is considered the threshold for determining the statistical significance.

4 Results and discussion

4.1 Cross-correlation between PM and meteorological parameters

Cross-correlation provides a way for comparing the two time-series and finding out the phase where the best match occurs, which is called 'lag.' The estimated cross-correlation coefficients between the two time-series data (PM and each of the meteorological parameters: wind speed, temperature, rainfall, relative humidity and solar radiation) are shown in Fig. 3. For each pair (PM vs. meteorological parameter), the magnitude and sign of correlation coefficients vary with lag times. The maximum coefficient and the lag value at which the strongest correlation was obtained are shown in Table 2. For example, $r = -0.570(1)$ between $\text{PM}_{2.5}$ and temperature depicts that the highest correlation of $r = -0.570$ which occurs between the two time-series at a lag of 1 day of $\text{PM}_{2.5}$ from temperature. Table 2 shows that temperature ($\text{PM}_{2.5}$: $r = -0.570(1)$, PM_{10} : $r = -0.501(1)$), wind speed ($\text{PM}_{2.5}$: $r = -0.367(0)$, PM_{10} : $r = -0.315(0)$) and relative humidity ($\text{PM}_{2.5}$: $r = -0.160(0)$, PM_{10} : $r = -0.295(0)$) have high

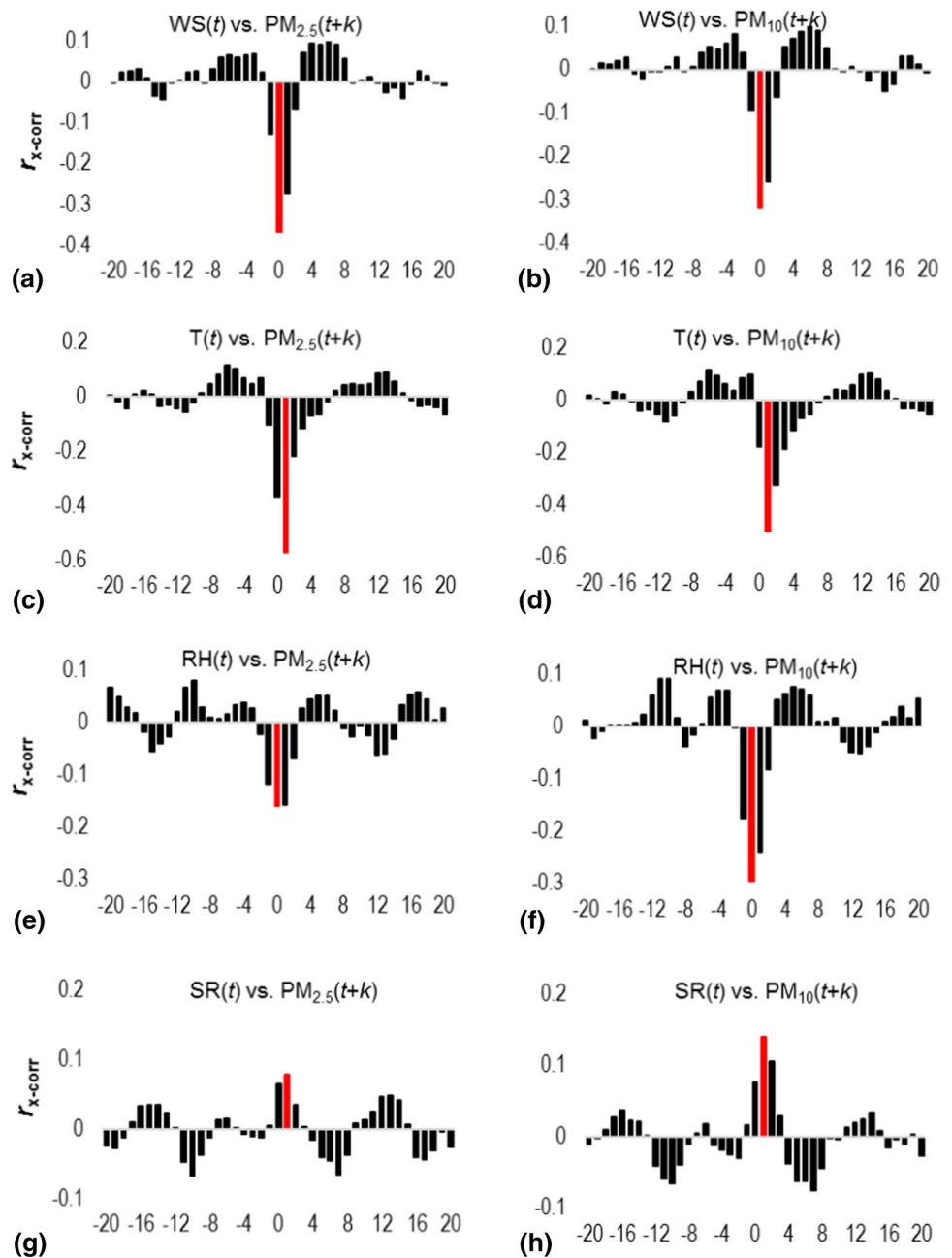
correlation with both $\text{PM}_{2.5}$ and PM_{10} . All meteorological parameters except solar radiation negatively correlate with both PM fractions. A possible reason for the negative correlation of wind speed with PM might be the dilution of particles at higher wind speeds (Hajiloo et al. 2019). The negative correlation with temperature may be explained by land surface temperature-induced atmospheric ventilation that allows larger diffusion of particles resulting in lower PM concentrations (Lu et al. 2012). According to Wang et al. (2016), high solar radiation favors atmospheric photochemical reactions leading to increased particulate formation, resulting in a positive correlation between PM and solar radiation. High rainfall and relative humidity can cause the removal of PM from the atmosphere; hence, an inverse relationship between PM and these parameters is observed. PM appears to have a weaker correlation with rainfall compared to relative humidity. A probable reason is that the high humidity conditions may have a more effective scavenging effect than rainfall intensity. Both impaction and nucleation mechanisms are accelerated in the presence of high humidity. Association of PM with all the meteorological parameters, except rainfall, is found to be significant at $p < 0.001$. Wind speed, relative humidity and rainfall show zero lag with PM, signifying that change in these parameters triggers a simultaneous response in PM. However, for both temperature and solar radiation, the maximum correlation with both PM fractions is found at a lag of 1 day, indicating a delayed response.

4.2 Seasonal cross-correlation

Some pollution sources in Dhaka city are strictly seasonal (e.g., brick kilns operate only in the dry seasons) (Islam et al. 2015). Ambient PM concentration also shows seasonality where the highest and lowest PM is seen in two distinct periods of the year. A seasonal cross-correlation can decouple its effects with those of meteorological parameters. We segregated the time-series data of PM and meteorological parameters to represent the four seasons: winter, pre-monsoon, monsoon and post-monsoon to perform season-wise cross-correlation. The maximum correlation coefficients with their respective lag periods are stated in Tables 3, 4, respectively, for $\text{PM}_{2.5}$ and PM_{10} . Only correlations during the same season (shown in bold in Tables 3, 4) are found to be significant ($p < 0.001$), and hence, only these cases are explained in the context of this study. Table 5 shows the qualitative summary of the seasonal association of PM with meteorological parameters with interpretations of the respective association.

The correlation of PM with wind speed is high during pre-monsoon ($r = -0.485(0)$ for $\text{PM}_{2.5}$; $r = -0.370(0)$ for PM_{10}) and monsoon ($r = -0.535(0)$ for $\text{PM}_{2.5}$; $r = -0.431(0)$ for PM_{10}) seasons which are characterized by high wind

Fig. 3 Cross-correlation coefficients ($r_{x\text{-corr}}$) of wind speed (a, b), temperature (c, d), relative humidity (e, f) and solar radiation (g, h) with $\text{PM}_{2.5}(t+k)$ and $\text{PM}_{10}(t+k)$ with respect to lag periods. Here, the unit of lag length is 1 day. The red bar indicates the maximum $r_{x\text{-corr}}$



velocities (mean wind speed 2.91 m s^{-1} and 2.56 m s^{-1} for pre-monsoon and monsoon, respectively). During monsoon, in addition to the dispersion due to high wind, the consistent rainfall and high humidity have a washing effect resulting in a reduction of PM. Besides, more friction velocity is required for dust resuspension under wet conditions during monsoon, which causes dust suppression (Li et al. 2017). That is why $\text{PM}_{2.5}$ and PM_{10} show a relatively stronger negative correlation with wind speed during monsoon than pre-monsoon. PM also shows high negative correlation with wind speed during winter ($r = -0.463(0)$ for $\text{PM}_{2.5}$; $r = -0.428(0)$ for PM_{10}). The low wind speed in this season slows down the

dispersal mechanism of PM concentration and favors the accumulation of PM in the atmosphere. Comparatively weak negative correlation is obtained between post-monsoon PM and wind speed ($r = -0.309(0)$ for $\text{PM}_{2.5}$; $r = 0.300(0)$ for PM_{10}). Since the post-monsoon PM level is almost half of the winter PM level, the accumulation effect of low wind speed is not as noticeable on PM as during winter. Between the two PM fractions, $\text{PM}_{2.5}$ shows a stronger negative correlation with WS for all seasons, which indicates that the dispersion of $\text{PM}_{2.5}$ due to wind is more pronounced.

Relative humidity negatively correlates with PM in all seasons, with a weaker correlation for $\text{PM}_{2.5}$ than PM_{10} . The

Table 2 Maximum annual cross-correlation coefficients between PM and meteorological variables in Dhaka with the corresponding lag period in days (in parenthesis)

Prediction variable	Maximum cross-correlation coefficient (lag)	
	PM _{2.5}	PM ₁₀
Wind speed	- 0.367 (0)**	- 0.315 (0)**
Temperature	- 0.570 (1)**	- 0.501 (1)**
Relative humidity	- 0.160 (0)**	- 0.295 (0)**
Solar radiation	0.078 (1)**	0.140 (1)**
Rainfall	- 0.052 (0)*	- 0.102 (0)*

Statistical significance indicators are as follows: ** $p < 0.001$, * $0.01 > p > 0.001$, otherwise $0.05 > p > 0.01$

reason could be that relative humidity accelerates adsorption, flocculation, gravitational settling and consequent reduction of particles, and it is more effective on PM₁₀ than on PM_{2.5} (Hamed et al. 2011). A strong correlation is obtained during monsoon and pre-monsoon seasons since the wet deposition effect of relative humidity is prominent during these periods. For PM₁₀, higher correlation is obtained for monsoon

($r = -0.426(0)$) than pre-monsoon ($r = -0.323(0)$) season (Table 4), which may be because moist condition during monsoon enhances coagulation-induced deposition of particles. Besides, dust emission, which primarily consists of PM₁₀, is suppressed as the minimum friction velocity required for dust rise increases under wet soil conditions (Hamed et al. 2011; Li et al. 2017). For PM_{2.5}, lower correlation is obtained for monsoon ($r = -0.276(0)$) than pre-monsoon ($r = -0.349(0)$) season (Table 3). A plausible reason can be the closure of kilns during the monsoon season. This argument may not be valid for PM₁₀ because monsoon PM₁₀ generation is higher than PM_{2.5} by the suspension of natural dust (PM₁₀) by the southwesterly wind.

A negative correlation is observed between rainfall and PM throughout the year except for the winter season (Tables 3, 4). As expected, precipitation shows the highest negative correlation with PM during monsoon season ($r = -0.156(0)$ for PM_{2.5}; $r = -0.202(0)$ for PM₁₀) when the intensity and duration of precipitation are the highest. The scavenging and wash-out effect on PM is the highest during this period (Guo et al. 2016).

The relationship between PM and temperature has a large seasonal influence. Temperature negatively correlates

Table 3 Seasonal cross-correlation analysis between meteorological parameters and PM_{2.5} in Dhaka showing maximum correlation coefficients and corresponding lag period in days (in parenthesis)

Meteorological parameters	Winter	Pre-monsoon	Monsoon	Post-monsoon
Wind speed				
Winter	- 0.463 (0)**	- 0.032 (0)	- 0.105 (0)	0.066 (0)
Pre-monsoon	0.054 (0)	- 0.485 (0)**	- 0.053(0)	0.050 (0)
Monsoon	0.010 (0)	0.022 (0)	- 0.535 (0)**	0.050 (0)
Post-monsoon	0.049 (0)	0.042 (0)	0.022 (0)	- 0.309 (0)**
Temperature				
Winter	- 0.425 (1)**	- 0.051 (0)	- 0.021 (0)	0.094 (0)
Pre-monsoon	0.058 (0)	- 0.405 (1)*	0.023 (0)	0.028 (0)
Monsoon	- 0.021 (0)*	0.050 (0)	0.133 (0)*	- 0.003 (0)
Post-monsoon	- 0.020 (0)*	- 0.038 (0)	0.058 (0)	- 0.425 (0)**
Relative humidity				
Winter	0.001 (0)	- 0.013 (0)	- 0.132 (0)	- 0.021 (0)
Pre-monsoon	- 0.061 (0)	- 0.349 (0)**	0.050 (0)*	- 0.031 (0)
Monsoon	0.003 (0)	0.0003 (0)	- 0.276 (0)*	- 0.051 (0)
Post-monsoon	0.045 (0)	0.030 (0)	- 0.073 (0)	- 0.263 (0)**
Solar radiation				
Winter	0.026 (0)	- 0.018 (0)	0.035(0)	0.030 (0)
Pre-monsoon	- 0.045 (0)	0.085 (0)	- 0.063(0)	0.024 (0)
Monsoon	0.0004 (0)	0.075 (0)	0.115 (0)*	0.014 (0)
Post-monsoon	0.042 (0)	0.023 (0)	- 0.048 (0)	0.192 (1)**
Rainfall				
Winter	- 0.092 (0)	- 0.108 (0)	- 0.055 (0)	- 0.025 (0)
Pre-monsoon	0.011 (0)	- 0.146 (0)**	0.066 (0)	0.057 (0)
Monsoon	0.043 (0)	0.055 (0)	- 0.156 (0)**	0.056 (0)
Post-monsoon	0.055 (0)	0.024 (0)	- 0.092 (0)	- 0.104 (0)*

Statistical significance indicators are as follows: ** $p < 0.001$; * $0.01 > p > 0.001$, otherwise $0.05 > p > 0.01$. Same season correlations are shown in bold

Table 4 Seasonal cross-correlation analysis between meteorological parameters and PM₁₀ in Dhaka showing maximum correlation coefficients and corresponding lag period in days (in parenthesis)

Meteorological parameters	Winter	Pre-monsoon	Monsoon	Post-monsoon
Wind speed				
Winter	– 0.428 (0)**	– 0.056 (0)	0.053 (0)	0.095 (0)
Pre-monsoon	– 0.086 (0)	– 0.370 (0)**	– 0.013 (0)	0.010 (0)
Monsoon	0.009 (0)	0.048 (0)	– 0.431 (0)**	0.029 (0)
Post-monsoon	0.050 (0)	0.036 (0)	0.025 (0)	– 0.300 (0)**
Temperature				
Winter	– 0.359 (1)**	– 0.081 (0)	0.060 (0)	– 0.114 (0)
Pre-monsoon	0.021 (0)	– 0.347 (1)**	– 0.030 (0)	0.025 (0)
Monsoon	0.027 (0)	– 0.088 (0)	0.263 (0)**	– 0.018 (0)
Post-monsoon	0.030 (0)	– 0.004(0)	0.087(0)	– 0.369(0)**
Relative humidity				
Winter	– 0.229 (0)**	0.025 (0)	– 0.051 (0)	0.011 (0)
Pre-monsoon	0.021 (0)	– 0.323 (0)**	0.034 (0)	0.032 (0)
Monsoon	0.012 (0)	– 0.020 (0)	– 0.426 (0)**	0.058 (0)
Post-monsoon	0.007 (0)	0.016 (0)	0.077 (0)*	– 0.310 (0)**
Solar radiation				
Winter	0.112 (0)*	– 0.010 (0)	0.016 (0)	0.024 (0)
Pre-monsoon	– 0.057 (0)	0.152 (1)*	– 0.042 (0)	0.014 (0)
Monsoon	0.039 (0)	0.020 (0)	0.259 (0)**	– 0.008 (0)
Post-monsoon	0.003 (0)	– 0.041 (0)	– 0.008 (0)	0.253 (1)*
Rainfall				
Winter	– 0.110 (0)*	0.017 (0)	– 0.015 (0)	0.013 (0)
Pre-monsoon	– 0.022 (0)	– 0.169 (0)**	– 0.030 (0)	0.055 (0)
Monsoon	0.077 (0)	– 0.050 (0)	– 0.202 (0)**	0.033 (0)
Post-monsoon	0.001 (0)	– 0.055 (0)	– 0.106 (0)	– 0.152 (0)*

Statistical significance indicators are as follows: ** $p < 0.001$; * $0.01 > p > 0.001$, otherwise $0.05 > p > 0.01$. Same season correlations are shown in bold

with both PM fractions throughout the year except during the monsoon. During monsoon, a positive correlation is observed with both particle fractions, although the coarse fraction has a stronger association with the temperature ($r = 0.133(0)$ for PM_{2.5}, $r = 0.263(0)$ for PM₁₀). Primary bioaerosol formation (such as pollen, fungal spores) is known to accelerate at high-temperature conditions and a warm rainy season (Barnpadimos et al. 2012; Ahmed et al. 2013). Besides, warm and humid conditions favor atmospheric chemical reactions, promoting new particle formation and conversion of gas to particle (Kanawade et al. 2014; Qi et al. 2015; Li et al. 2017). Temperature and PM synchronize with zero lag during post-monsoon ($r = -0.425(0)$ for PM_{2.5}, $r = -0.369(0)$ for PM₁₀) while temperature leads PM by 1 day during winter ($r = -0.425(1)$ for PM_{2.5}, $r = -0.359(1)$ for PM₁₀) and pre-monsoon ($r = -0.405(1)$ for PM_{2.5}, $r = -0.347(1)$ for PM₁₀). In winter and post-monsoon, the atmospheric temperature remains low, and boundary layer height is reduced, creating stable atmospheric conditions. These conditions favor particulate accumulation since ventilation is weak (Ji et al. 2014; Sun et al. 2016; Toro et al. 2019). This results in elevated PM levels

and, consequently, an inverse relationship between temperature and PM. In addition, contrary to the monsoon season, a higher correlation is observed for PM_{2.5} than PM₁₀ during winter and post-monsoon seasons. This could be due to a higher prevalence of fine particles generated by solid waste open burning in dumping areas and fossil fuel burning in kilns, both dominant activities in Dhaka city at that time. During pre-monsoon, the inverse correlation might be due to higher atmospheric ventilation. Diurnal increase in temperature during the day causes an increase in boundary layer height, allowing PM dilution, thus favoring diffusion of particles and subsequent PM reduction (Lu et al. 2012).

A positive correlation is obtained between PM and solar radiation throughout the year. This positive association can be explained by the phenomena of new particle formation in ambient air, favored by high solar radiation. Most of these new particles form through vapor condensation on pre-existing nuclei or atmospheric ions. One of the key elements is sulfuric acid, formed in the air through the oxidation of SO₂ by OH- molecule, which bonds with NH₃, amine bases and low volatility organic molecules to form new particles. The photochemical reactions of nucleation and vapor

Table 5 Summary of the associations (type and strength of correlation) of PM with meteorological parameters and interpretation of the association

Meteorological parameter	Season	Type of correlation with PM	Strength of correlation	Interpretation of the association
Wind speed	Winter	Negative	Strong	Calm wind-induced PM accumulation
	Pre-monsoon	Negative	Strong	Strong wind-induced PM dispersion
	Monsoon	Negative	Strongest	Strong wind-induced PM dispersion, wet condition-induced dust suppression
	Post-monsoon	Negative	Weak	Negligible PM accumulation under low wind speed
Relative humidity	Winter	Negative	Weak	Negligible effect of relative humidity on PM
	Pre-monsoon	Negative	Strong	Relative humidity-induced PM deposition
	Monsoon	Negative	Strong	Relative humidity-induced PM deposition, wet condition-induced dust suppression (prominent for PM ₁₀)
Rainfall	Post-monsoon	Negative	Strong	Relative humidity-induced PM deposition
	Winter	Negative	Weak	Negligible effect of rainfall on PM
	Pre-monsoon	Negative	Strong	Rainfall induced PM wash-out
	Monsoon	Negative	Strongest	Rainfall induced PM wash-out
Temperature	Post-monsoon	Negative	Moderate	Rainfall induced PM wash-out
	Winter	Negative	Strong	Low temperature-induced PM accumulation
	Pre-monsoon	Negative	Moderate	High temperature-induced PM dispersion
	Monsoon	Positive	Moderate	Bioaerosol formation under warm, humid condition
Solar radiation	Post-monsoon	Negative	Strong	Low temperature-induced PM accumulation
	Winter	Positive	Weak	Negligible effect of solar radiation on PM
	Pre-monsoon	Positive	Weak	Negligible effect of solar radiation on PM
	Monsoon	Positive	Strong	Solar radiation-induced new particle formation
	Post-monsoon	Positive	Strong	Solar radiation-induced new particle formation

condensation are facilitated when solar radiation remains high (Vehkamaki et al. 2004; Guo et al. 2012; Kerminen et al. 2018). The correlation between PM and solar radiation is found to be comparatively higher during monsoon and post-monsoon season especially for PM₁₀ (monsoon: $r=0.115(0)$ for PM_{2.5}, $r=0.259(0)$ for PM₁₀; post-monsoon: $r=0.192(1)$ for PM_{2.5}, $r=0.253(1)$ for PM₁₀). Hygroscopic growth of condensation species and rapid conversion to coarser particles may be responsible for this association (Friedlander 2000; Hamed et al. 2007; Satheesh et al. 2008). The pre-monsoon correlation between PM and solar radiation ($r=0.085(0)$ for PM_{2.5}, $r=0.152(1)$ for PM₁₀) is weak compared to monsoon and post-monsoon. The characteristics of the pre-monsoon air mass, low vegetation cover and an internal association between other parameters may affect this correlation. The correlation between PM and solar radiation is observed to be weak during winter ($r=0.026(0)$ for PM_{2.5}, $r=0.112(0)$ for PM₁₀). Low solar radiation during the winter might be responsible for such a correlation.

4.3 Comparison with similar studies worldwide

We compared our results with similar analysis carried out in different cities to assess whether geographic location

plays a role in determining PM-meteorology interactions. An account of the associations (expressed as correlation coefficients) found between PM with meteorological parameters for different cities in the USA, Canada, Mexico, Turkey, Egypt, China, Vietnam and India is presented in Table 6. North American cities in the USA and Canada experienced high PM during summer seasons, whereas the cities in Asian and European countries (Turkey, Egypt, China, Vietnam, India, and Bangladesh) exhibited a high pollution load during the winter season. The composition of PM, atmospheric circulation pattern, surface temperature and corresponding pressure systems could be responsible for these variable episodes of pollution load. A negative correlation with temperature is observed for cities in Egypt, Turkey, China, Nepal, and India, whereas a positive correlation is observed for cities in the USA, Greece, Germany and Spain. India shows a negative correlation between solar radiation and PM while Spain, Germany and Bangladesh show the reverse. Different weather and atmospheric circulation patterns, pressure systems, latitude–longitude, angle of incident solar radiation and location-specific chemical composition of aerosols may play a significant role in such associations. The cities in China, Nepal, India, Egypt, and Turkey lie primarily in

Table 6 Correlation coefficients of PM_{2.5} and PM₁₀ with meteorological parameters in different regions^a

	Method	T	RH	WS	SR	R	References
PM_{2.5}							
Greece (winter)	PC	0.46	–	– 0.54	–	–	Chaloulakou et al. (2003)
USA (yearly)	LC	0.4–0.7 ^b	– 0.1 to – 0.15 (South) ^b , 0.05 to 0.14 (North) ^b	– 0.05 to 1.0 ^a	–	–	Tai et al. (2010)
Spain (yearly)	LC	– 0.016	0.048	– 0.496	0.048	–	Galindo et al. (2011)
Turkey (winter)	PC	– 0.324	– 0.108	– 0.350	–	–	Akyuz and Cabuk (2009)
China (yearly)	LC	– 0.293	– 0.41	–	–	–	(Wang et al. 2015)
Nepal (yearly)	PC	–	–	–	–	–	(Giri et al. 2008)
India (yearly)	SRC	– 0.27	0.10	– 0.60	– 0.06	–	Gupta et al. (2006)
Bangladesh (yearly)	XC	– 0.570	– 0.160	– 0.367	0.078	– 0.052	This study
PM₁₀							
Spain (yearly)	LC	0.601	0.189	– 0.334	0.699	–	Galindo et al. (2011)
Germany (yearly)	SRC	0.17	– 0.15	– 0.49	0.28	– 0.38	Gietl and Klemm (2009)
Greece (yearly)	PC	0.39	–	– 0.43	–	–	Chaloulakou et al. (2003)
Turkey (winter)	PC	– 0.155	– 0.237	– 0.409	–	–	Akyuz and Cabuk (2009)
Egypt (yearly)	PC	– 0.48	0.252	–	–	–	Elminir (2005)
China (yearly)	LC	–	– 0.501	0.407	–	–	Wang et al. (2015)
Nepal (yearly)	PC	– 0.358	– 0.539	0.162	–	– 0.358	Giri et al. (2008)
India (yearly)	SRC	– 0.22	0.10	– 0.52	– 0.05	–	Gupta et al. (2006)
Bangladesh (yearly)	XC	– 0.501	– 0.295	– 0.315	0.140	– 0.102	This study

PC pearson correlation, LC linear correlation, SRC spearman rank correlation, XC maximum annual cross-correlation

^aStrength of correlation can vary with the methodology (e.g., averaging period, size of the dataset) and/or PM compositions. Therefore, correlation coefficient values mentioned in this table cannot be directly compared between studies

^bThe study in the USA presented coefficients for ~200 sites. Range of the correlation values is presented for this specific study. ‘South’ means coefficient values at Southern region of the USA and ‘North’ means coefficient values at Northern region of USA

the subtropical to Mediterranean region, where generally low-pressure system prevails, and the incoming solar radiation strikes the surface of the earth directly, causing comparatively humid and warm weather conditions. On the other hand, the cities in the USA, Greece, Germany and Spain mostly fall under temperate to Mediterranean regions, characterized by the high-pressure system and smaller angle of incident solar radiation. During the winter season in the former group of cities, a decrease in temperature was associated with an increase in PM, leading to a negative correlation. In the summer season of the latter group of cities, an increase in temperature was associated with an increase in particulates leading to a positive correlation. No such trend corresponding to the region is observed for relative humidity and PM interaction, though most locations exhibit a negative correlation.

A negative correlation is obtained for all regions for wind speed and rainfall, which may indicate their dispersal and scavenging effect, respectively, on PM. The association of PM with most meteorological parameters in Bangladesh has similarities to other countries located in the subtropical to Mediterranean climate regions. However, it is essential to

indicate that apart from Bangladesh, all correlation values presented in Table 6 are Pearson or Spearman rank correlation; hence, lag or lead of the corresponding time-series data were not considered.

4.4 The relative contribution of meteorological parameters to PM variation

We applied multiple linear regression (MLR) to understand how much variability in PM can be explained by meteorological parameters and their relative contribution to this variability. Tables 7, 8 summarize the results of single and multiple linear regression analysis with meteorological parameters corresponding to PM_{2.5} and PM₁₀, respectively. In regression analysis, the variables wind speed, temperature, relative humidity, solar radiation, and rainfall are denoted as WS, T, RH, SR and R, respectively. We also used T(1) and SR(1), which denotes temperature and solar radiation lead of 1 day, as predictor variables because of their significant association with PM (see Sects. 4.1 and 4.2). In both instances, T(1) has been found to have the most influence on PM concentration, individually explaining 60% and

Table 7 Linear regression analysis results for daily PM_{2.5} concentration and meteorological variables

Prediction variables	Adjusted <i>r</i> ²	PRESS	<i>p</i> value
T(1)	0.60	1977	< 0.0001
T	0.54	2258	< 0.0001
WS	0.27	3616	< 0.0001
RH	0.13	4290	< 0.0001
SR	0.07	4600	0.0071
R	0.06	4652	0.0215
SR(1)	0.06	4642	0.0179
T + WS + RH + SR + R	0.71	1434	< 0.0001
T × RH + WS × SR + RH + WS + WS × T + SR	0.74	1301	< 0.0001
T(1) + WS + RH + SR + R	0.73	1346	< 0.0001
T × RH + WS × T(1) + T(1) + WS + RH × SR + R	0.76	1172	< 0.0001

WS wind speed, T temperature, RH relative humidity, SR solar radiation, R rainfall, T(1) temperature with 1 day lead, SR(1) solar radiation with 1 day lead

Table 8 Linear regression analysis results for daily PM₁₀ concentration and meteorological variables

Prediction variables	Adjusted <i>r</i> ²	PRESS	<i>p</i> value
T	0.40	7203	< 0.0001
T(1)	0.49	6103	< 0.0001
WS	0.24	9103	< 0.0001
RH	0.24	9181	< 0.0001
R	0.07	11,173	0.0063
SR	0.03	11,700	0.2111
SR(1)	0.02	11,766	0.2641
T × RH + WS + WS × T + SR + RH × SR + R	0.69	3704	< 0.0001
T(1) + WS + RH + SR + R	0.69	3703	< 0.0001
T(1) × RH + WS × SR + R + SR + WS + WS × T(1) + RH	0.73	3290	< 0.0001

WS wind speed, T temperature, RH relative humidity, SR solar radiation, R rainfall, T(1) temperature with 1 day lead, SR(1) solar radiation with 1 day lead

49% of variability for PM_{2.5} and PM₁₀, respectively. Therefore, it was the primary choice as the prediction variable. Other parameters were included sequentially based on their influence and significance. Individual contributions from WS and RH were less pronounced compared to T or T(1) but significant (*p* < 0.0001). Compared to other parameters, SR and R had a minor contribution in explaining the variability of PM. A linear combination of T(1), WS, RH, SR and R explained 73% and 69% of the variability of PM_{2.5} and PM₁₀, respectively. It is possible that individual meteorological parameters can interact with each other and can affect PM concentration. For example, an increase in T decreases RH by increasing the moisture-holding capacity of the surrounding air. In addition, WS and RH may vary simultaneously based on the atmospheric pressure system.

Therefore, in the regression model, we further allowed terms to denote interaction between meteorological parameters, and Tables 7, 8 show only those interaction terms which were significant at a 99% confidence level. For PM_{2.5}, the inclusion of interaction terms T × RH, WS × T(1), RH × SR increased the predictability of the model (minimum value of 1172 obtained for PRESS), which allowed the meteorological parameters to explain 76% of the variability. It means that to modulate PM_{2.5}, WS appears to associate with T while RH interacts with both T and SR. The presence of the term WS × T(1) may indicate that the nature of WS may influence the effect of T on PM_{2.5} and vice versa. For example, thermally induced atmospheric ventilation, a primary modulator of PM variation, can be significantly influenced by calm wind conditions (Yang and Li 2011). Besides, the term T × RH may indicate that ambient T can affect atmospheric moisture-holding capacity and thus can influence the effect of RH on PM_{2.5}. Similar interactions may exist for other parameters, which combinedly influence PM_{2.5} concentrations. Similarly, for PM₁₀, the addition of interaction terms (WS × R, T(1) × RH, WS × T(1)) into the model improves the predictability from 69% to 73% (Table 8). A study in the USA showed that daily variation in meteorology could explain up to 50% of daily PM_{2.5} variability (Tai et al. 2010).

5 Conclusion

In this study, a 5 year dataset of PM and meteorological parameters from 2013 to 2017 was analyzed to determine the PM dependency on atmospheric conditions in Dhaka city. The extent of seasonal PM dependency on weather parameters was assessed using seasonal cross-correlation and regression analysis. Multiple linear regression reveals that in Dhaka city, meteorological variation can explain up

to 76% and 73% of the daily variability of $PM_{2.5}$ and PM_{10} , respectively. Cross-correlation analysis shows that wind speed, relative humidity and temperature are significant contributors to PM variability. Seasonal cross-correlation analysis shows that wind speed, relative humidity and rainfall show negative and solar radiation shows positive correlation with $PM_{2.5}$ and PM_{10} throughout the year. Temperature shows a negative correlation with $PM_{2.5}$ and PM_{10} throughout the year except for the monsoon season. PM accumulation under calm wind during winter and post-monsoon and PM dispersion under high wind during pre-monsoon and monsoon season could be responsible for the negative correlation with wind speed. The negative correlation of PM with relative humidity and rainfall may refer to the scavenging effect of water droplets, which is maximum during monsoon season. A positive correlation of PM with solar radiation, which is maximum in monsoon and post-monsoon season, may refer to the phenomena of new particle formation under the presence of solar radiation. The negative correlation of PM with temperature may refer to PM accumulation under low temperature during winter and post-monsoon and PM dispersion under high temperature during pre-monsoon season. In addition, a positive correlation of PM with temperature during monsoon season suggests bioaerosol formation phenomena under warm, humid conditions. These results from our analysis show that meteorological parameters drive the PM variation in Dhaka city with strong seasonal influence. Future studies can be conducted to determine whether such influences have similar effects in other cities with different PM profiles, different weather characteristics, or other externalities (e.g., different pollution sources, geographical differences). Lagged correlations using hourly resolution data could be used to analyze into day-time vs. night-time interaction between PM and meteorology, which could be useful in gaining insight into the evolution of PM with respect to atmospheric dispersion conditions. Our study highlights the need to understand the time-dependent effect of meteorological parameters on PM variation and its importance in formulating air pollution mitigation strategies.

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Data availability The datasets analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no conflict of interest.

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