Airborne Particulate Pollution Measured in Bangladesh from 2014 to 2017

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ABSTRACT

Recently, the World Health Organization ranked Narayanganj, Chittagong, and Dhaka among the top 25, 40, and 45 cities, respectively, for high ambient PM2.5 concentrations. Bangladesh has instituted an air quality monitoring system operated by the Department of Environment. PM2.5 and PM10 were measured hourly from January 2014 through December 2017 in Dhaka, Gazipur, Narayanganj, Chittagong, Sylhet, and Barisal. All sites registered concentrations for both pollutants that exceeded the 24-h Bangladesh National Ambient Air Quality Standards. The particulate matter (PM) concentrations varied significantly seasonally and with different diel patterns from city to city. The highest concentrations were observed during the winter, typically when wind speeds and mixed layer heights are low and pollutant concentrations are increased by transport from the northwest. The PM2.5 concentrations from the 1st quarters of 2014 and 2015 were compared to assess whether political unrest that appeared to reduce vehicular moment to very low levels affected the observed values. However, the PM2.5 concentrations were statistically similar at the Dhaka, Narayanganj, and Sylhet sites and different for the Gazipur, Chittagong, and Barisal locations. Thus, the PM2.5 concentrations during the political unrest in the 1st quarter of 2015 were not consistently lower across the measurement sites. These results indicate that vehicular emission contributions to PM2.5 concentrations are smaller than in the past, which agrees with recent source apportionment studies showing that brick kilns have become the dominant source of PM.

Keywords: Air quality; PM2.5; PM10; Temporal patterns; Meteorology.

INTRODUCTION

Air pollution, particularly PM2.5, is a critical health issue around the big cities and industrial areas of the world. Out of 2,975 cities in the world, the World Health Organization placed Narayanganj, Chittagong, and Dhaka among the top 25, 40, and 45 cities, respectively, as having the worst air pollution (WHO, 2016). In addition, Dhaka (Begum and Hopke, 2018) and other cities in Bangladesh have for many years been experiencing some of the highest PM concentrations among the world’s cities. Rana et al. (2016b) found annual PM2.5 concentrations about six times greater than the national standards of Bangladesh even if the concentrations in Dhaka have significantly dropped since the 1990s (Begum and Hopke, 2018).

Many studies have shown that with respect to health concerns and reduced urban visibility, particulate matter (PM) is the most important pollutant (WHO, 2016). Major sources of PM in Dhaka are diesel-powered and gasoline vehicles and brick kilns (Salam et al., 2003; Begum et al., 2005, 2014; Begum and Hopke, 2019). The annual growth rate in the number of register vehicles over the last 10 years ranged between 7 and 16% (Begum et al., 2011a). However, the switch of most cars to compressed natural gas (CNG) and implementation of other traffic related policies have resulted in lower PM concentrations than would have otherwise been expected (Begum and Hopke, 2018, 2019). Black carbon (BC) is one of the primary emissions of diesel and other vehicles particularly when they are poorly maintained and from brick kilns. However, the use of heavy-duty diesel vehicles has been limited in Dhaka to 22:00 until 06:00 the following morning. Thus, brick kilns have become the more important BC source (Begum and Hopke, 2019). There is increased interest in urban BC concentrations because of the likelihood of its effects on human health (Ramanathan and Carmichael, 2008).

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Different studies have shown that vehicular emissions have effectively contributed to ambient PM$_{2.5}$. These emissions may happen directly or indirectly. The direct emission sources are vehicular exhaust (Sagebiel et al., 1996; Mulawa et al., 1997; Handler et al., 2008), mechanical wear of tires and brakes (Garg et al., 2000; Amato, 2018), the ejection of particles from pavement (Kupiainen et al., 2005; Amato, 2018), unpaved road shoulders (Moosmuller et al., 1998), and by re-suspension processes (Nicholson et al., 1989; Sternbeck et al., 2002; Amato, 2018). Alternatively, indirect emission sources include reactive gases, both organic and inorganic that form secondary particulate matter via atmospheric transformations (Seinfeld and Pandis, 2016).

According to the Bangladesh Road Transport Authority, the number of vehicles in Bangladesh increased from about 1.5 million in 2010 to over 3.4 million vehicles by March 2018 (BRTA, 2018).

Receptor modelling studies to estimate PM pollution in the Dhaka Metropolitan Area (DMA) showed an average contribution of 30–40% originating in brick kilns and a declining influence from motor vehicles (Begum et al., 2005, 2014; Begum and Hopke, 2019). Previous studies have indicated the transboundary source contributions to PM pollution could be an influential factor and thus, should be considered for managing air quality in Bangladesh (Begum et al., 2011b; Rana et al., 2016a; Ommi et al., 2017). Transboundary source regions, specifically, northwestern India, Nepal and its neighboring areas, and the Indian state of West Bengal, were identified as the most probable zones that might have contributed to PM pollution in Gazipur and Dhaka (Rana et al., 2016a; Ommi et al., 2017). At present, PM is a global concern of people living in urban area. Therefore, the present study seeks to verify the contribution of vehicular emissions to PM$_{2.5}$ in Bangladesh; secondly, to estimate the concentration of PM$_{2.5}$ during a political crisis when vehicular numbers were dramatically reduced; and finally, to measure the seasonal variations of PM$_{2.5}$ concentrations in Bangladesh.

**MATERIALS AND METHODS**

**Sampling Duration and Location**

Data from the ambient air quality monitoring stations operated by the Department of Environment were used in this study. The sampling period of PM$_{2.5}$ was from January 2014 through December 2017. One potentially interesting aspect of this period is the possibility of quantifying the differences between PM$_{2.5}$ concentrations from the 1st quarter of 2014 to those from the 1st quarter of 2015. Because of political unrest, traffic flow was very low around the country in the 1st quarter of 2015 (TDS, 2015). The impact of this situation on PM$_{2.5}$ concentrations was evaluated in this study. Currently there are eleven stations in Bangladesh. The monitoring data obtained from six stations were used in this study. The other five stations’ data were not available due to analyzer operational problems. All the six continuous air monitoring station (CAMS) locations and the analyzers used for measuring PM$_{2.5}$ concentrations are presented in Table 1 and Fig. 1. Met One Model BAM-1020 beta attenuation monitors (BAMs) were used to measure hourly PM$_{2.5}$ and PM$_{10}$ concentrations. The Met One BAM-1020 is a U.S. Environmental Protection Agency Federal Equivalent Method (FEM) monitor for PM$_{2.5}$ and is widely used for PM monitoring. All BAMs were operated at the flow rate of 16.7 L min$^{-1}$ and calibrated by using a bubble flow meter (Gibirometer-2 system, Sensidyne, USA). Each station is also equipped with meteorological monitors for wind speed and direction, temperature, relative humidity, solar insolation, and barometric pressure.

**Data Processing**

The air quality data generated at the monitoring stations is centrally retrieved into the central data station at the Department of Environment (DoE)’s head office using EnVIEW 2000 software and SQL database. All data are scrutinized for outliers and invalid values. Subsequently, the data are checked, compiled, processed, and analyzed statistically to obtain annual means, standard deviations, temporal coverage, etc. of the measured pollutants. While processing the air quality data, if 75% of the data availability for any parameter in a day were not measured at a given station due to force majeure like power failure, analyzer failure, etc., those values are considered as non-representative and excluded from ambient air quality data for that day. The statistical analyses were performed with XLSTAT (Addinsoft), QI Macros 2015, and SigmaPlot V14 (Systat).

**Table 1. CAMS locations and analyzer used to measure PM.**

<table>
<thead>
<tr>
<th>Station</th>
<th>Coordinates</th>
<th>Inlet height</th>
<th>Method</th>
<th>Monitor</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chittagong</td>
<td>22.323178 N 91.802289 E</td>
<td>~7.0 m</td>
<td>Beta gauge</td>
<td>BAM-1020</td>
<td>Met One Instruments, Inc.</td>
</tr>
<tr>
<td>Dhaka</td>
<td>23.780678 N 90.355444 E</td>
<td>~7.0 m</td>
<td>Beta gauge</td>
<td>BAM-1020</td>
<td>Met One Instruments, Inc.</td>
</tr>
<tr>
<td>Sylhet</td>
<td>24.890236 N 91.866833 E</td>
<td>~8.0 m</td>
<td>Beta gauge</td>
<td>BAM-1020</td>
<td>Met One Instruments, Inc.</td>
</tr>
<tr>
<td>Barisal</td>
<td>22.709925 N 90.362339 E</td>
<td>~7.0 m</td>
<td>Beta gauge</td>
<td>BAM-1020</td>
<td>Met One Instruments, Inc.</td>
</tr>
<tr>
<td>Narayanganj</td>
<td>23.627456 N 90.507456 E</td>
<td>~7.0 m</td>
<td>Beta gauge</td>
<td>BAM-1020</td>
<td>Met One Instruments, Inc.</td>
</tr>
<tr>
<td>Gazipur</td>
<td>23.99131 N 90.420086 E</td>
<td>~7.0 m</td>
<td>Beta gauge</td>
<td>BAM-1020</td>
<td>Met One Instruments, Inc.</td>
</tr>
</tbody>
</table>
Quality Assurance and Quality Control (QA/QC) of Data and Management

QA/QC is an essential part of any monitoring system. To obtain reliable data from the air quality monitoring stations, proper QA/QC measures have to be in place as this data will be used to support policy decisions. QA/QC is a program of activities which ensures that overall measurements meet pre-defined standards of quality, with a stated level of confidence. The DoE has developed a QA/QC protocol along with documentation that is followed at all monitoring stations to obtain harmonized reliable air quality data. This process covers calibration, servicing and repair of instruments/equipment, and evaluation of status of ambient air quality monitoring stations in the network. A weekly inspection checklist describes the overall status of the CAMS and Zero/Span checks, which ensures the validity of the calibration of each of the analyzers. Particulate BAM monitors were calibrated using standard foils of known areal mass density. Servicing included preventive maintenance and repair of the analyzers was performed by trained service engineers under a maintenance contract with the local manufacturer’s representative. The overall service and repair is centrally coordinated to ensure quality.

RESULTS AND DISCUSSION

Meteorological Data Analysis

Fig. 2 shows a summary of the meteorological variable values from the beginning of the 1st quarter of 2014 to the end of the 1st quarter of 2015 from the multiple CAMS to show typical seasonal cycles. There were problems with the meteorological system at Sylhet and thus, it has been excluded from this figure. During the winter, very low wind speeds are observed with extended periods of calm winds. Mixed layer heights are also low producing very poor dispersion conditions (Muntaseer Billah Ibn Azkar et al., 2012). Analyzing hourly wind direction, the total contributions were 18.8% from the northeast, 33.6% from the southeast, 25% from the southwest, and 22.6% from the northwest (Fig. 2(a)). The Bay of Bengal is situated to the south of the country and has a major influence on southeasterly and southwesterly winds.

Fig. 2(b) shows the daily average relative humidity (RH) measured in Dhaka, Gazipur, Chittagong, and Barisal. During the winter, the RH readings are generally lower than the RH in the monsoon season. Fig. 2(c) shows the daily average wind speed at five different CAMS. The wind speeds typically varied from 0.5 to 3 m s⁻¹, but in winter, wind speeds are lower. Fig. 2(d) shows the daily average temperature at the five CAMS. In winter, the temperature varies from 15 to 25°C while in summer and monsoon, the temperature varies from 25 to 35°C.

PM Concentrations

Summary statistics for the six sites are provided in Table 2 for 1-h and 24-h average PM concentrations. Fig. 3 shows the 24-h averaged PM$_{2.5}$ and PM$_{10}$ data from each CAMS relative to the 24-h Bangladesh National Ambient
Fig. 2. Meteorological observation monitored in different CAMS during the 1st quarter of 2014 to the 1st quarter of 2015 concerning: (a) hourly wind direction data percentage contribution among the CAMS; (b) daily average relative humidity (%); (c) daily average wind speed (m s\(^{-1}\)); (d) daily average temperature.

Table 2. Summary statistics for hourly and daily PM\(_{2.5}\) and PM\(_{10}\) concentrations (µg m\(^{-3}\)) at the 6 monitoring sites.

<table>
<thead>
<tr>
<th>Hourly values</th>
<th>Dhaka</th>
<th>Gazipur</th>
<th>Narayanganj</th>
<th>Chittagong</th>
<th>Sylhet</th>
<th>Barisal</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM(_{2.5})</td>
<td>PM(_{10})</td>
<td>PM(_{2.5})</td>
<td>PM(_{10})</td>
<td>PM(_{2.5})</td>
<td>PM(_{10})</td>
<td>PM(_{2.5})</td>
</tr>
<tr>
<td>Number of hourly values</td>
<td>27932</td>
<td>28820</td>
<td>24224</td>
<td>24144</td>
<td>22466</td>
<td>28235</td>
</tr>
<tr>
<td>% Missing</td>
<td>20%</td>
<td>18%</td>
<td>31%</td>
<td>31%</td>
<td>36%</td>
<td>19%</td>
</tr>
<tr>
<td>Minimum</td>
<td>4.0</td>
<td>9.0</td>
<td>4.0</td>
<td>9.0</td>
<td>4.0</td>
<td>9.0</td>
</tr>
<tr>
<td>25th Percentile</td>
<td>30.8</td>
<td>62.0</td>
<td>30.7</td>
<td>57.2</td>
<td>27.2</td>
<td>81.5</td>
</tr>
<tr>
<td>Median</td>
<td>47.8</td>
<td>97.9</td>
<td>56.9</td>
<td>99.9</td>
<td>56.9</td>
<td>156.0</td>
</tr>
<tr>
<td>75th Percentile</td>
<td>114.9</td>
<td>202.0</td>
<td>131.9</td>
<td>210.2</td>
<td>152.0</td>
<td>289.7</td>
</tr>
<tr>
<td>Maximum</td>
<td>500</td>
<td>955</td>
<td>497</td>
<td>947</td>
<td>501</td>
<td>956</td>
</tr>
</tbody>
</table>

Air Quality Standard (BNAAQS) values of 65 µg m\(^{-3}\) for PM\(_{2.5}\) and 150 µg m\(^{-3}\) for PM\(_{10}\). Gazipur, Narayanganj, and Barisal have higher median values than the other three sites. However, all the sites had maximal values around 900 µg m\(^{-3}\) and a significant number of days in which the PM concentrations exceed the BNAAQS limits. Thus, all sites are out of compliance with the standard requirements.

There are large fractions of missing data, with the lowest value being 18% of PM\(_{10}\) in Dhaka and the highest being 49% of PM\(_{2.5}\) values in Barisal. Although every effort was made to collect data sets as complete as possible, there was the loss of considerable data resulting from intermittent power losses from the grid. Outages include planned rolling blackouts and unanticipated power disruptions. In addition to the loss of data during the outages, there is also a recovery period during which the data are unreliable. A reliable supply of filter tapes and the need to send defective units out of the country for repairs also resulted in data gaps.

The quarterly distributions of PM\(_{2.5}\) and PM\(_{10}\) for Dhaka are shown in Fig. 4 as box and whisker plots. The comparable plots for the other five locations are presented in the supplemental material file as Figs. S1–S5. The distributions are positively skewed with the mean greater than the median and with many extreme values in every quarter.

Quarters 2 and 3 (April to September) have significantly lower PM concentrations driven by increased precipitation, wind speeds, and mixed layer heights during these months as well as reduced burning for space heating and substantial reductions in brick kiln emissions during the rainy periods when the areas hosting the kilns were flooded.
Fig. 3. Time series plots of the 24-h PM$_{2.5}$ and PM$_{10}$ concentrations for all 6 sites. The lines represent the 24-h BNAAQS levels.
Fig. 4. Box and whisker plots showing the quarterly distributions for PM$_{2.5}$ (top) and PM$_{10}$ (bottom) measured at the Dhaka CAMS. The lines represent the corresponding BNAAQS levels.

At the Barisal site, there were significant problems measuring the PM$_{2.5}$ concentrations in the final quarter of 2016. Additionally, PM$_{10}$ data for the entire 2016 year were also absent at that station. The reason was the difficulty in obtaining repairs to instruments when they fail. The final quarter PM$_{2.5}$ data from Chittagong are also missing due to equipment problems.

**Temporal Variations in PM Concentrations**

The temporal variability for PM$_{2.5}$ in Dhaka is summarized in Fig. 5 while that for PM$_{10}$ in Dhaka is given in Fig. 6. The analogous plots for Gazipur, Narayanganj, Chittagong, Sylhet, and Barisal are shown in Figs. S5–S10 for PM$_{2.5}$ and Figs. S11–S15 for PM$_{10}$.

There are distinct differences between the diel patterns for PM$_{2.5}$ and PM$_{10}$ in Dhaka. PM$_{10}$ has more distinct morning rush hour and evening (18:00–24:00) peaks. There is less of a decrease in PM$_{2.5}$ concentrations during the early morning hours. For month-to-month changes, PM peaks in the winter particularly January and February, but PM$_{10}$
Fig. 5. Temporal variations of PM$_{2.5}$ concentrations measured in Dhaka.

Fig. 6. Temporal variations of PM$_{10}$ concentrations measured in Dhaka.
also has a peak in late pre-monsoon periods (May and June). Winter is the period with the lowest wind speeds and mixed layer heights as well as increased transport of transboundary pollutants on northwesterly winds (Rana et al., 2016a; Ommi et al., 2017). The pre-monsoon peaks in PM are likely due to additional soil that is aerosolized during the hot and dry weather that precedes the monsoon rains. There are also differences in day-of-the-week patterns with PM$_{2.5}$ peaking on Wednesday while PM$_{10}$ has its highest values on Sunday with a secondary peak on Wednesday. The PM$_{2.5}$ pattern is similar to other urban patterns with a midweek peak. Being a predominantly Muslim country, Friday has less traffic and activity as does Saturday with work typically resuming on Sunday.

The patterns for the other Dhaka area sites (Gazipur (Figs. S6 and S11)) and Narayanganj (Figs. S7 and S12)) are similar, but at Gazipur, there is a greater decrease in concentration during the early morning period than Dhaka or Narayanganj. The monsoon peaks in Gazipur are shifted later (August for PM$_{2.5}$ and August–September for PM$_{10}$). There are 13 cement factories and 320 brick kilns in Narayanganj and 410 brick kilns around Gazipur compared to 200 kilns in Dhaka (ILO, 2014; CemNet, 2018). Although many kilns shut down for the wet season when their land floods, it appears that there may be some cyclical activity during the summer giving rise to the strong monsoon PM peaks north and south of Dhaka.

The diel patterns for Chittagong (Figs. S8 and S13) show a stronger morning rush hour peak for PM$_{2.5}$ and peak in both PM sizes after midnight suggesting activity during the early morning period. A major industry in Chittagong is ship salvage and there are 8 cement plants and over 1000 brick kilns (ILO, 2014; CemNet, 2018). The monthly patterns in Chittagong are different from those in Dhaka and its surrounding areas with more uniform mean values and higher monsoon values than in winter. Also, there is a November minimum in PM$_{2.5}$ but not in PM$_{10}$. The rise of PM$_{2.5}$ in December may be due in part to PM transported from both east and west of Bangladesh (Ommi et al., 2017).

Sylhet is in the northeast of the country, and its diel patterns suggest limited traffic influence (lack of a strong morning rush hour peak) and significant heating/cooking emissions with a large overnight peak at around 22:00 for both size fractions. The monthly patterns for both sizes are very similar with the highest values during the winter when there would be significant biomass burning for space heating (Begum et al., 2009; Chowdhury et al., 2012). The day-of-week patterns peaked on Sunday but also had Friday peaks.

**Did Political Disruption Affect Air Quality?**

To test the hypothesis that decreased traffic during the 1st quarter of 2015 resulted in lower PM$_{2.5}$ concentrations, Kruskal-Wallis ANOVA on ranks analysis by quarter was run on the hourly data from each site and the quarter-by-quarter comparisons were made using 95% Bonferroni intervals. The results are presented in Table 3. In all cases, the 2014 PM$_{2.5}$ values are higher than the 2015 concentrations.

<table>
<thead>
<tr>
<th>Site</th>
<th>Difference</th>
<th>+/- Limits</th>
<th>Significant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dhaka</td>
<td>667.993</td>
<td>1469.02</td>
<td>No</td>
</tr>
<tr>
<td>Gazipur</td>
<td>1321.31</td>
<td>1274.07</td>
<td>Yes</td>
</tr>
<tr>
<td>Narayanganj</td>
<td>727.001</td>
<td>1478.76</td>
<td>No</td>
</tr>
<tr>
<td>Chittagong</td>
<td>1193.36</td>
<td>785.289</td>
<td>Yes</td>
</tr>
<tr>
<td>Sylhet</td>
<td>880.8601</td>
<td>802.342</td>
<td>Yes</td>
</tr>
</tbody>
</table>

There are clearly mixed results with Gazipur, Chittagong, and Barisal showing statistically significant differences while the other three sites do not. Dhaka, Gazipur, and Narayanganj are all within the Dhaka Metropolitan Area such that major changes in traffic emissions would likely be reflected at all three sites. In addition, the recent source apportionment work has suggested that the influence of traffic on PM concentrations has been substantially diminished in recent years (Begum and Hopke, 2019). To examine the potential decrease in the impacts of vehicle emissions in more detail, a Mann-Whitney rank sum test was performed for each of the source apportioned mass contributions in Dhaka estimated by Begum and Hopke (2019). There was no statistically significant difference in the motor vehicle contributions between the 1st quarters of 2014 and 2015. The only one with a significant difference was road dust, and again the 2014 value was higher than in 2015 suggesting some reduction in traffic related PM$_{2.5}$. It is not possible to perform similar analyses on the differences seen between these quarterly PM values in Chittagong and Barisal. It appears that the political disturbances may have had a minor influence on PM$_{2.5}$ concentrations but not uniformly among all of the measurement locations.

**CONCLUSIONS**

The major contributors to PM$_{2.5}$ in Bangladesh have been established as brick kiln and motor vehicle emissions along with soil and road dust (Salam et al., 2003; Begum and Hopke, 2019). The PM$_{2.5}$ concentrations were below BNAQS during the monsoon season (the 2nd and 3rd quarters of the year), whereas they were far above them during the rest of the year. Although the PM$_{2.5}$ concentrations decreased between 2014 and 2015 at all of the sites, they were significantly lower only in Gazipur, Chittagong, and Barisal, with an appreciable difference solely in the contribution from road dust. To further reduce PM concentrations, the Government of Bangladesh should emphasize efficient management of other sources, particularly the implementation of cleaner technology in all brick kiln operations across the country.

**ACKNOWLEDGMENTS**

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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