



Ambient Air Quality in Dhaka Bangladesh over Two Decades: Impacts of Policy on Air Quality

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ABSTRACT

Samples of the fine and coarse fractions of airborne particulate matter (PM) were collected using a 'Gent' stacked filter unit in a semi-residential area of Dhaka, Bangladesh from December 1996 through September 2015. The site is located at the Atomic Energy Centre, Dhaka University Campus that is a relatively low traffic area. Many policies have been implemented during this period to clean the air of Dhaka. Among them, bans on leaded-gasoline and two-stroke engines were implemented, and a policy regarding green technology for brick burning is in progress. To observe the effects of the policy implementations, analyses were performed on this long-term (December 1996 to September 2015) data set of PM₁₀, PM_{2.5}, black carbon (BC), and lead (Pb). Annual average concentrations of PM₁₀, PM_{2.5}, BC, and Pb were computed. These long-term data show that the air quality of Dhaka has been stable over the past decade even though economic activity and the number of sources including passenger cars and brick kilns, are increasing.

Keywords: PM₁₀; PM_{2.5}; Black carbon (BC); Lead (Pb); Long-term monitoring.

INTRODUCTION

More than one-third of Bangladesh's population live in large urban areas. By 2050, at least half of the population will be urbanized. The highest concentration of population growth has been in and around Dhaka (latitude 23.77°N, longitude 90.38°E), the capital of Bangladesh. There has been an eightfold increase in population since 1970, and it now stands at more than 12 million, making it the eighth largest city in the world. It is likely to become the third largest city by 2020 when its population reaches approximately 20 million. In South Asia, airborne particulate matter (PM₁₀ and PM_{2.5}) is a major concern because of its high ambient concentrations and documented impact on morbidity and premature mortality (Kojima *et al.*, 2000).

Prior to 1999, very limited efforts were made to control vehicular and industrial emissions. There was no air quality management system in Bangladesh to address air pollution problems. Only since that time has the government established some regulatory and institutional frameworks to manage the urban air quality problems. To improve air quality within Dhaka and to ultimately attain U.S. EPA as

well as the Bangladesh National Air Quality Standards, control strategies have been promulgated.

The primary focus of air quality management efforts has been on Dhaka. Dhaka is highly congested with many private and public motor vehicles including many private buses and taxis. Another major PM source is brick kilns around Dhaka. With widespread construction, there is a high demand for building bricks. However, the kilns can generally operate only during the winter period because of flooding of the area during other times of the year. Other PM sources include resuspension from dusty, unpaved or partially paved roads, and refuse burning by slum dwellers.

Before banning the two-stroke engines in 2003, about 50% of particulate matter smaller than 2.5 micron (PM_{2.5}) came from vehicular emissions (Begum *et al.*, 2004). Thus, vehicles were believed to constitute the dominant source of air pollution in Dhaka (Begum *et al.*, 2004, 2005, 2006a). Two pollutants of concern in the 1990s were lead and particulate matter. Lead in gasoline was phased out of use in 1999 (Biswas *et al.*, 2003).

With respect to particulate matter, the government has been active in addressing the significant contribution from two-stroke, three-wheel vehicles, commonly known as baby taxis. These small vehicles were gross emitters, with one baby taxi emitting as much as 10 times more particulate matter (PM) and hydrocarbons than a comparable four-stroke vehicle (Rahman *et al.*, 2001; Kajima *et al.*, 2002).

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The use of excess, low quality lube oil and the lack of proper maintenance practices produced much of the high PM emissions. Prior to September 2002, very many two-stroke engine three-wheelers were used in Dhaka with the number of vehicles in this class estimated to be around 65,000. They provide useful, low cost, point-to-point transportation, but emitting significant black smoke, white smoke, and hydrocarbons. Emission inventory calculations showed that these vehicles contributed about 40% of the vehicular air pollution for PM₁₀. To address pollution from baby taxis, several actions were undertaken by the Bangladesh Government under the Air Quality Management Project (AQMP). This project included auto clinics, promotion of 2T lube oil, and finally, phased replacement of two-stroke engines with four-stroke and compressed natural gas (CNG) engines.

To implement this phase out, the Ministry of Communications announced an order banning all two-stroke engine baby taxis in Dhaka by December 31, 2002. The first phase that included most 1995 vintage vehicles or older that were to be retired on September 1, 2002. The remaining estimated 6,500 vehicles were retired on December 31, 2002. However, administrative and other problems led to an unsuccessful phase out of the older vehicles. Because of firm Government action, all of the two-stroke three wheelers were removed from Dhaka by the end of December 2002. New cars are generally CNG powered and the gasoline vehicles are now equipped with air pollution control devices. CNG-powered cars, busses, and trucks have been introduced, and industrial sources are slowly being regulated. The government is also trying to improve brick burning technology through Clean Air and Sustainable Environment

(CASE) project implemented by the Department of Environment, Ministry of Forests and Environment. Because of these control strategies, air quality in Dhaka has slowly and steadily improved (Begum and Biswas, 2004; Begum *et al.*, 2004; 2005; 2006a, b, 2011a, b, 2013, 2014, 2018).

To understand the extent of the problem and to develop effective mitigation strategies, air quality monitoring data is essential. The concentration record over time provides valuable information about the extent of air pollution and its sources. In this report, the relationships between policy implementations and ambient air quality in Dhaka measured between 1996 and 2015 are presented.

MATERIALS AND METHOD

PM Sampling and Analysis

Sampling was performed at semi-residential site in Dhaka using a 'Gent' stacked-filter sampler (Hopke *et al.*, 1997; Begum and Biswas, 2005) capable of collecting air particulate samples in coarse (2.5–10 µm) and fine (2.5 µm,) size fractions. Fig. 1 shows the location of the sampling site in Dhaka. The sampler was placed on the flat roof of the Atomic Energy Centre, Dhaka (AECD) campus building. The roof height was 5 m and the intake nozzle of the sampler was located 1.8 m above the roof. The intake was about 80 m away from the roadside. The sampler was placed so that the airflow around it was unobstructed. Twenty-four-hour representative samples were collected twice a week, generally on Sunday and Wednesdays. No sampling was performed on Fridays. The effective sampling time was varied between 6 and 20 h (depending on season) distributed uniformly over 24 h a day to avoid filter

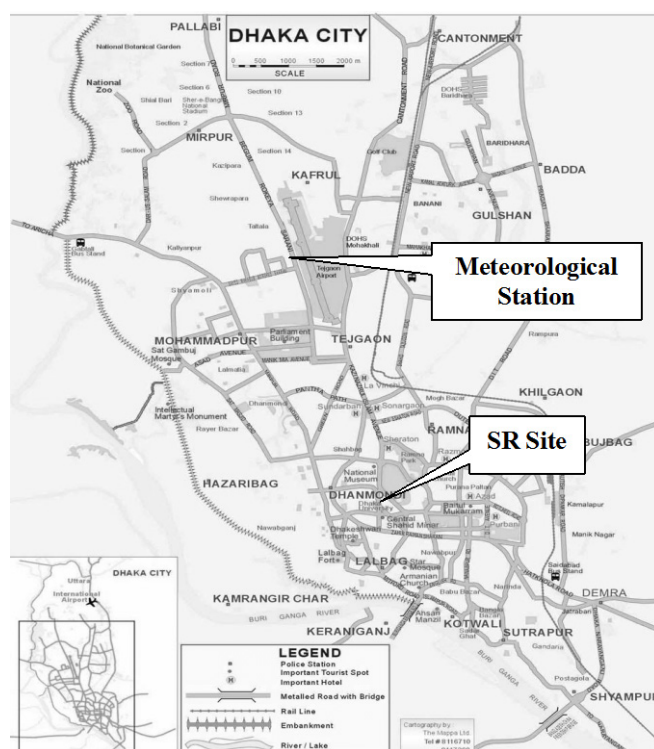


Fig. 1. Map showing sampling location at Dhaka, Bangladesh.

clogging and so that the flow rate (17 L min^{-1}) remains within the prescribed limits of the sampler. This ensured proper size fractionation and collection efficiency (Begum and Biswas, 2005). There were generally no samples collected on Thursdays or Fridays. Samples were most commonly collected on Sunday and Wednesday.

The samples were collected on Nuclepore filters with $8 \mu\text{m}$ pores for the coarse fractions and $0.4 \mu\text{m}$ pores for the fine fractions. After sampling, the sample holder (Stack Filter Unit) was brought in the AECD (Atomic Energy Centre, Dhaka) Laboratory for retrieval of the filters and the samples were kept in airtight petri slides and stored in air-conditioned room (temperature 22°C and relative humidity of 50% approximately). The post weighing of the samples was usually completed within one month of collection (Begum *et al.*, 2006c). Crosschecking of the sampling method with an Airmetrics MiniVol sampler showed that the GENT sampler has comparable sampling efficiency (Begum *et al.*, 2004c).

PM Mass and BC Determination

Mass and BC were measured in the AECD laboratory. The PM masses of both the coarse and fine fractions were determined by weighing the filters before and after exposure using a microbalance (METTLER Model MT5) and maintaining room temperature at 22°C and relative humidity at 50%. Both the coarse ($\text{PM}_{10-2.5}$) and fine ($\text{PM}_{2.5}$) samples were equilibrated at constant humidity and temperature in the balance room for at least 24 hours before each weighing. A Po-210 (alpha emitter) electrostatic charge eliminator (STATICMASTER) was used to eliminate the static charge accumulated on the filters before each weighing. Quality control in filter weighing was assured by using appropriate laboratory and field blanks.

The concentration of black carbon (BC) in the fine fraction of the samples was determined by reflectance measurement using an EEL-type Smoke Stain Reflectometer (Coulson and Ellison, 1963; Commins and Waller, 1967; Biswas *et al.*, 2003). Secondary standards of known black carbon concentrations are used to calibrate the reflectometer.

Source Apportionment

Prior studies have reported source apportionments based on data from this site up to 2009 (Begum *et al.*, 2013). Compositional analysis has been made on these samples using ion beam analysis as described by Begum *et al.* (2004, 2006a). The resulting data for 2010 to 2015 including the BC concentrations were subjected to source apportionment analysis using PMF2 (Paatero, 1997) as previously described. Uncertainties were estimated using the procedure of Polissar *et al.* (1998) and the choice of the number of factors was based on the distributions of scaled residuals and the interpretability of resulting profiles.

Meteorological Conditions

In Bangladesh, the climate is characterized by generally high temperatures and high humidity much of the year with distinctly different seasonal variations in precipitation. The year can be divided into four seasons: pre-monsoon

(March–May), monsoon (June–September), post-monsoon (October–November), and winter (December–February) (Salam *et al.* 2003). Winter is characterized by dry soil conditions, low relative humidity, scanty rainfall, and low northwesterly prevailing winds. Rainfall and wind speed become moderately strong and relative humidity increases in the pre-monsoon season with prevailing south to southwesterly (marine) winds. During monsoon, the wind speed increase further, and air masses are strongly marine in nature. In the post-monsoon season, rainfall and relative humidity decrease as does wind speed. Wind direction starts shifting back to northeasterly. The meteorological data used in this study was obtained from a local meteorological station, located about 5 kilometers north of the semi-residential site.

RESULTS AND DISCUSSION

PM Concentrations

Table 1 shows the arithmetic and geometric means of the mass concentrations with the 95% confidence intervals for $\text{PM}_{2.5}$ and PM_{10} in samples collected at the SR site. In this study, all samples were collected on weekdays. The yearly average values for both PM_{10} and $\text{PM}_{2.5}$ masses (Table 2) are much higher than the 2012 USEPA standards (US EPA, 2012) as well as the Bangladesh National Ambient Air Quality Standard (BNAAQs) for $\text{PM}_{2.5}$ which is set at $50 \mu\text{g m}^{-3}$ and $15 \mu\text{g m}^{-3}$, respectively. The PM_{10} mass concentrations are also higher than the WHO guideline range ($60\text{--}90 \mu\text{g m}^{-3}$). Here all of the samples are collected during the weekdays. The distributions of sample masses of PM_{10} and $\text{PM}_{2.5}$ collected at semi-residential area (SR) of Dhaka are plotted as ‘box and whisker’ plots shown in Fig. 2. The line in each box represents the median of the particle mass concentration. The range of the box depicts the

Table 1. Airborne particulate concentrations ($\mu\text{g m}^{-3}$) in PM_{10} , $\text{PM}_{2.5}$ and BC concentrations sampled during the study periods at semi-residential areas, in Dhaka.

Sample	SR
PM_{10}	
Arithmetic mean	96.3
95% Confidence interval	92.9–99.6
Geometric mean	76.8
95% Confidence interval	76.7–76.9
Min-Max	10.1–426
$\text{PM}_{2.5}$	
Arithmetic mean	34.6
95% Confidence interval	33.4–35.8
Geometric mean	27.9
95% Confidence interval	27.8–28.0
Min-Max	2.33–220
BC	
Arithmetic mean	10.0
95% Confidence interval	9.52–10.4
Geometric mean	7.52
95% Confidence interval	7.42–7.63
Min-Max	0.39–101

Table 2. Average air particulate matter mass concentration ($\mu\text{g m}^{-3}$) and $\text{PM}_{2.5}/\text{PM}_{10}$ and $\text{BC}/\text{PM}_{2.5}$ ratio during the collection period in semi-residential area in Dhaka.

Year	PM_{10}	$\text{PM}_{2.5}$	BC	$\text{PM}_{2.5}/\text{PM}_{10}$	$\text{BC}/\text{PM}_{2.5}$
1996–97	92.5 ± 54.2	44.9 ± 26.4	15.8 ± 8.88	0.51 ± 0.13	0.37 ± 0.10
1997–98	98.5 ± 62.7	49.2 ± 28.9	21.0 ± 13.1	0.54 ± 0.15	0.45 ± 0.18
1998–99	132 ± 88.0	67.2 ± 40.8	25.3 ± 22.0	0.56 ± 0.13	0.37 ± 0.18
1999–00	94.1 ± 64.1	46.3 ± 25.8	15.1 ± 9.93	0.56 ± 0.13	0.34 ± 0.13
2000–01	93.2 ± 82.7	35.1 ± 28.3	11.8 ± 8.77	0.42 ± 0.14	0.39 ± 0.15
2001–02	73.4 ± 48.1	25.7 ± 16.9	8.48 ± 4.74	0.39 ± 0.14	0.35 ± 0.09
2002–03	81.7 ± 45.7	32.9 ± 19.5	9.10 ± 6.88	0.42 ± 0.12	0.28 ± 0.11
2003–04	71.7 ± 48.6	23.9 ± 14.8	7.89 ± 5.82	0.36 ± 0.12	0.33 ± 0.12
2004–05	67.1 ± 37.4	26.7 ± 12.5	8.45 ± 6.43	0.44 ± 0.15	0.33 ± 0.20
2005–06	112 ± 85.1	36.4 ± 30.5	10.3 ± 8.12	0.35 ± 0.11	0.30 ± 0.10
2006–07	90.8 ± 46.9	31.5 ± 13.5	9.60 ± 4.81	0.38 ± 0.12	0.32 ± 0.11
2007–08	102 ± 51.9	35.4 ± 17.8	8.30 ± 4.08	0.37 ± 0.10	0.25 ± 0.08
2008–09	123 ± 81.8	41.2 ± 23.4	9.24 ± 5.77	0.38 ± 0.12	0.27 ± 0.15
2009–10	113 ± 82.7	33.5 ± 19.1	10.5 ± 4.94	0.34 ± 0.13	0.36 ± 0.14
2010–11	121 ± 70.2	38.2 ± 20.1	8.39 ± 4.59	0.35 ± 0.10	0.23 ± 0.08
2011–12	82.7 ± 54.0	17.0 ± 13.2	3.90 ± 2.55	0.23 ± 0.09	0.25 ± 0.09
2012–13	109 ± 78.3	33.8 ± 26.2	6.11 ± 4.02	0.33 ± 0.11	0.20 ± 0.08
2013–14	82.5 ± 43.7	30.2 ± 19.6	6.43 ± 3.90	0.38 ± 0.13	0.23 ± 0.08
2014–15	100 ± 58.7	32.7 ± 21.3	6.85 ± 4.69	0.35 ± 0.12	0.21 ± 0.09
BNAQS	50	15	-	-	-

bounds of the 25th and 75th percentile of the data. Outliers in each data set are also shown as individual points. This site is consistently out of attainment of the Bangladesh NAAQS for both $\text{PM}_{2.5}$ and PM_{10} .

The yearly average $\text{PM}_{2.5}/\text{PM}_{10}$ and $\text{BC}/\text{PM}_{2.5}$ ratios are given in Table 2. It is observed that both the PM_{10} and $\text{PM}_{2.5}$ mass concentration decreased at the SR site. The decreasing trend in the $\text{PM}_{2.5}/\text{PM}_{10}$ ratio suggests that the coarse fraction in the PM has decreased less than the $\text{PM}_{2.5}$.

Vehicles normally produce more fine particles ($\text{PM}_{2.5}$) than coarse ones ($\text{PM}_{2.5-10}$ particles) that mostly originate from mechanical processes (Begum *et al.*, 2004). However, the roads are not well maintained nor effectively swept resulting in resuspended dust. Source apportionment studies (Begum *et al.*, 2004, 2014) found that about 15% of fine particle are soil dust. Fig. 3 shows the frequency distribution of the daily $\text{PM}_{2.5}/\text{PM}_{10}$ and $\text{BC}/\text{PM}_{2.5}$ mass ratios at SR site during the measurement period (Begum *et al.*, 2008). The maxima were found to be around 0.4 and 0.3 for the $\text{PM}_{2.5}/\text{PM}_{10}$ and $\text{BC}/\text{PM}_{2.5}$ mass ratios, respectively. This result indicates that for most days, about 40% of the PM mass concentrations are fine particles with aerodynamic diameter less than 2.5 μm , which are mainly of anthropogenic and urban activities and as well as about 30% of BC concentrations are in $\text{PM}_{2.5}$ concentration. In Dhaka, there are significant emissions from automobiles and other anthropogenic activities related to the extremely high population density. Biomass/coal burning for cooking and in the brick kilns around the city contribute significantly to these emissions (Salam *et al.*, 2003). Because of the proximity of roadways in SR area, the influence of traffic induced coarse dust from abrasion and resuspension is obvious and causes a shift of the maximum to 0.4. This is plausible because mechanically produced particles, particularly dust

resuspension, depend not only on the vehicle frequency but also on the condition of the roadway (e.g., clean/dirty, wet/dry).

Seasonal Variations of PM_{10} and $\text{PM}_{2.5}$

Fig. 4 shows the time series plots of PM_{10} , $\text{PM}_{2.5}$ and BC concentrations at the sampling site. It can be seen from Fig. 4 that characteristic seasonal variations are observed for the PM_{10} and $\text{PM}_{2.5}$ with elevated concentrations during the winter. The high peaks during the winter are caused by seasonal fluctuations of the emissions, and meteorological effects including wind direction and mixed layer heights. Fig. 5 shows the typical wind direction pattern calculated from wind direction data obtained from the Bangladesh Meteorological Department, Dhaka in different seasons in Bangladesh. During the wintertime, the wind comes mainly from north and northwest directions. At the same time, there is a lower mixed layer height and thus, poorer dispersion conditions for local sources. There is also a contribution of $\text{PM}_{2.5}$ mass transported from the north and northwesterly directions (Begum *et al.*, 2011c; Ommi *et al.*, 2017). These results indicate that PM concentrations in winter are also influenced by transboundary air pollution.

Mandated Changes in Motor Vehicles and their Influence on Air Quality

Gasoline engines contribute to air pollution by emitting high levels of particulate matter (especially two-stroke engines), carbon monoxide, nitrogen oxides, and volatile organic compounds. Diesel engines also emit high levels of particulate matter including BC, nitrogen oxides, volatile organic compounds, and sulfur oxides. The allowed concentration of sulfur in Bangladesh diesel fuel was 5000 ppm with a planned reduction to 500 in 2014 and

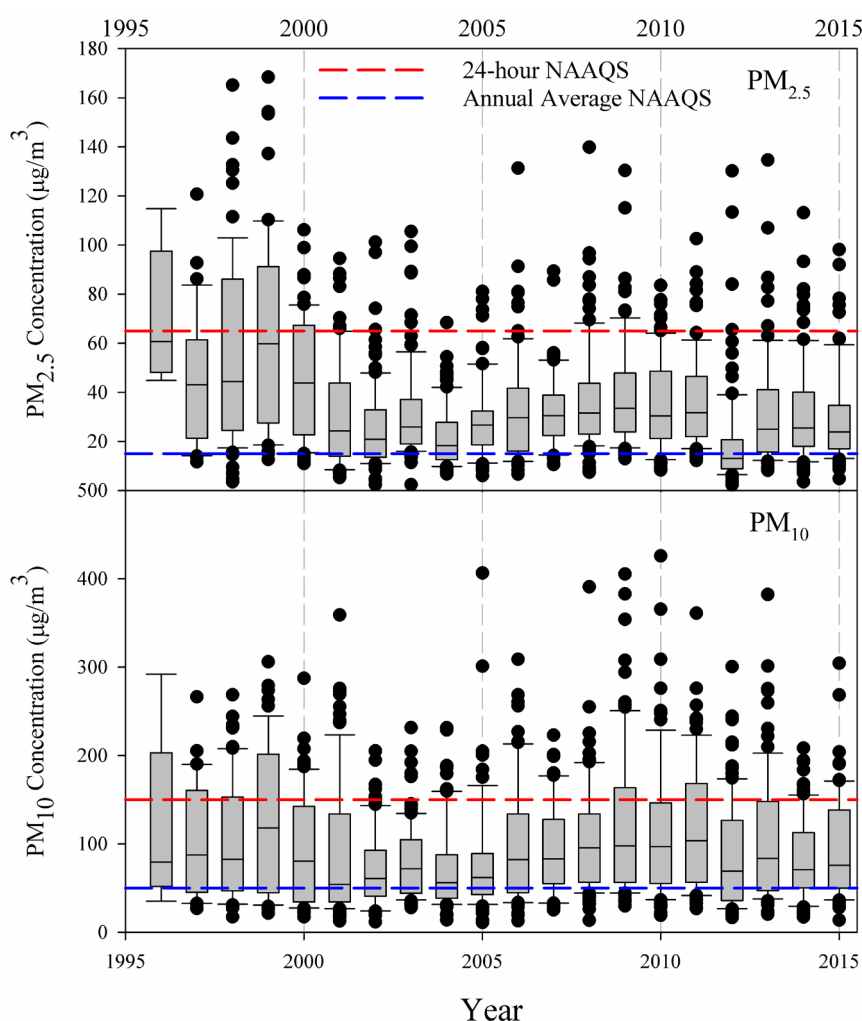


Fig. 2. Box-whisker plots of the time series of $PM_{2.5}$ (top) and PM_{10} (bottom) measured in Dhaka. The red line shows the 24-hour NAAQS limit while the blue line shows the annual average NAAQS limit.

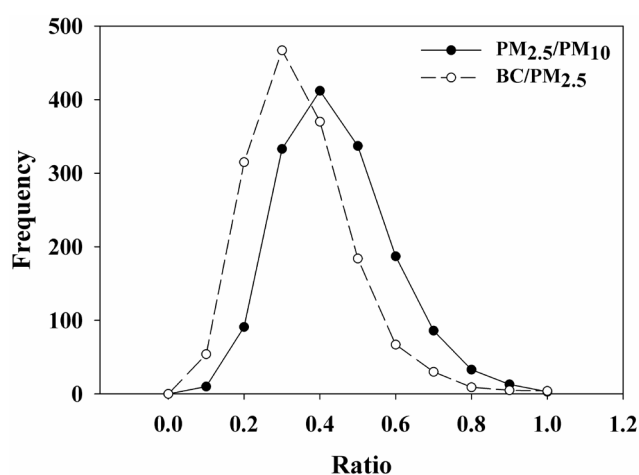


Fig. 3. Frequency distribution of the daily $PM_{2.5}/PM_{10}$ and $BC/PM_{2.5}$ mass ratios.

to 350 in 2019 (DOE, 2012). However, by 2015, the limit on sulfur in diesel fuel had been reduced to 2500 ppm and recommendations were made to import 500 ppm S fuel by

2016 (DOE, 2015). Actual imports of 500-ppm S fuel began in 2015 and even lower sulfur fuel has been imported in 2017. From prior source apportionment studies (Begum *et al.*, 2004, 2005, 2006a), it was found that about 50% of $PM_{2.5}$ comes from vehicular emissions (Begum *et al.*, 2004). Thus, vehicles constituted a dominant source of air pollution in Dhaka (Begum *et al.*, 2004, 2005, 2006a). Much of the governmental actions to date have focused on vehicular emission control (World Bank, 2004; DOE, 2012). Pollutants of concern in the 1990s were lead and particulate matter. Lead in gasoline was phased out of use in 1999 (Biswas *et al.*, 2003). With respect to particulate matter, the government has been active in addressing significant contribution from two-stroke engine powered three-wheel vehicles, commonly known as baby taxis. These little vehicles were gross emitters, with one baby taxi emitting as much as 10 times more particulate matter (PM) and hydrocarbons than a comparable four-stroke vehicle (Rahman *et al.*, 2001; Kajima *et al.*, 2002). As noted above, prior to September 2002, ~65,000 two-stroke engine three-wheelers were used in Dhaka. Their removal at the end of 2002 had a dramatic impact on $PM_{2.5}$ concentrations, particularly in high traffic

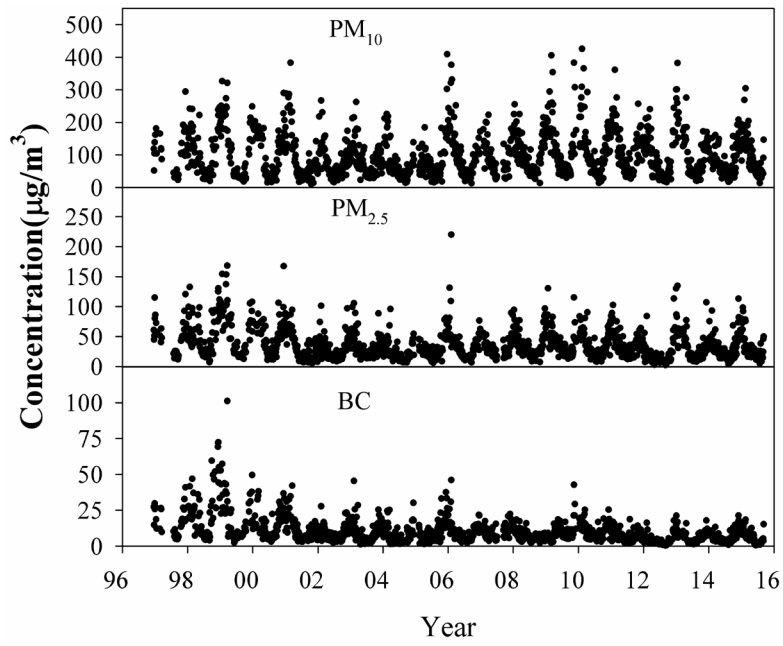


Fig. 4. Time series plot of PM₁₀, PM_{2.5}, and BC concentration.

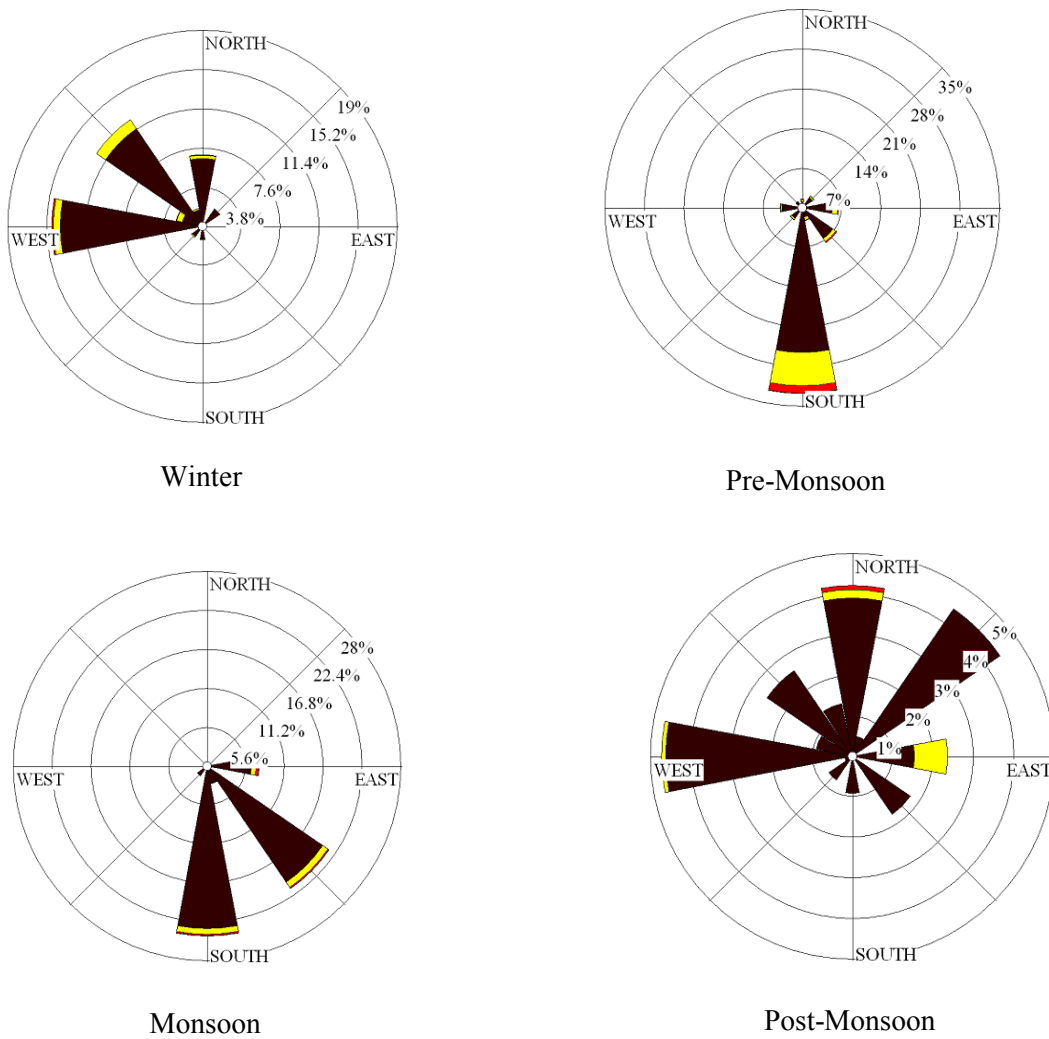


Fig. 5. Seasonal wind direction patterns for Dhaka.

areas where a decrease of 25% was measured following the removal of the baby taxis from the roads (Begum *et al.*, 2006b). The other sources of particulate matter emissions are brick kiln around Dhaka that mainly operate during the winter period, resuspension from all the dusty unpaved roads and refuse burning by slum dwellers.

It has been observed that fine particulate matter is slowly decreasing over this period due to government policy interventions (Fig. 2 and Table 2). The first step was to reduce emissions through the proper tuning and repairing of vehicles. This process was begun in 2000. For this purpose, a series of auto clinics were conducted in which three-wheelers were checked for emissions free of charge, drivers were given a simple health examination, and information was provided to the drivers on how to operate their vehicles in a manner to minimize emissions. In 2001, the government took steps to minimize the PM emissions from vehicles by prohibiting the production, blending, import, and marketing of mineral oil without additives and set minimal standards for lubricants for two-stroke and four-stroke engine vehicles. Finally, on January 1, 2003, two-stroke engines, old buses (20 years), and trucks (25 years) were taken off the roads.

The use of CNG for passenger vehicles and heavy-duty trucks and busses has reduced the PM emissions from motor

vehicles. Heavy-duty diesel vehicles have been banned from roads in Dhaka except between 10 PM and 6 AM. The DOE (2012) reported that roadside measurements found that more than 60% of the diesel fleet fail to meet free acceleration smoke emissions standards. Fig. 6 (top) shows the time series of BC annual distributions. There is a sharp decrease beginning in 2000 and then a more gradual decline with time as CNG vehicles replaced gasoline and diesel. There was not a major change in BC concentrations as a result of the 2-stroke taxi ban since those vehicles are generally not major BC sources.

The results of the source apportionment given in Table 3 show the influence of policy adaptation on motor vehicles. Details of the apportionment of the 2009 to 2015 data are provided in the supplemental material file. The earliest source apportionment results from 2001 to 2002 (Begum *et al.*, 2004) showed that vehicles normally produced about 50% of fine particles ($PM_{2.5}$ particles). The most recent source apportionment data (Begum *et al.*, 2013) (Table 3) shows that the contribution of BC from motor vehicles has decreased following CNG adoption in 2003. It has also found that the highest contribution of BC in 2001 to 2002 was from motor vehicles including two stroke engines (Begum *et al.*, 2004b). Air quality policy actions were taken for PM as well as BC emission reductions from motor vehicles. The

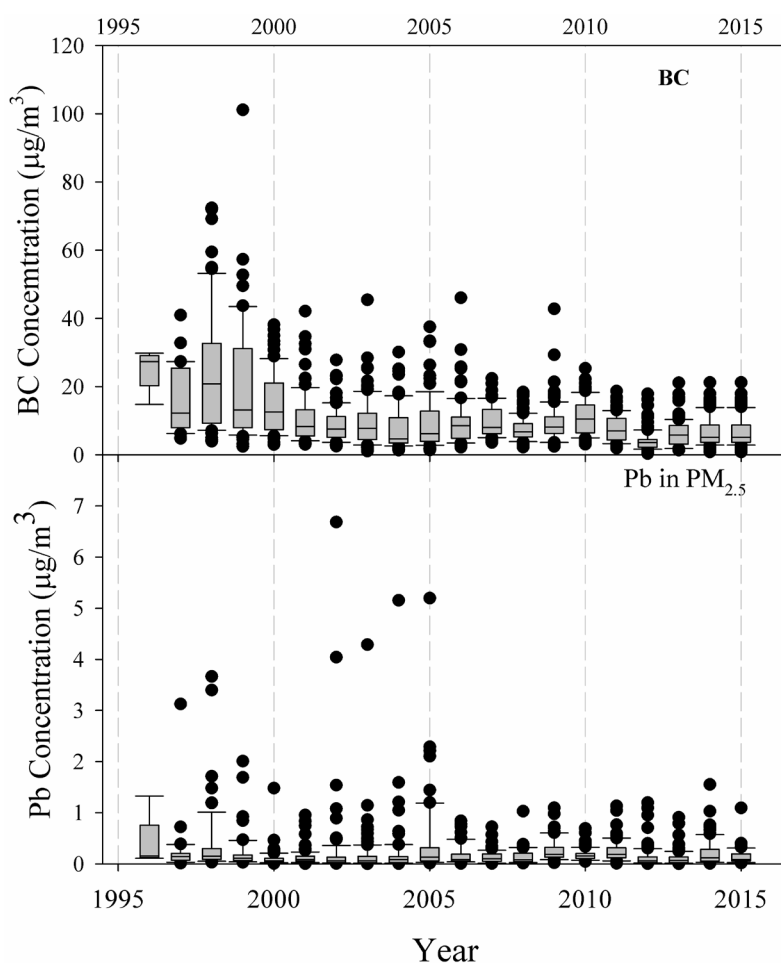


Fig. 6. Distributions of BC and Pb in $PM_{2.5}$ concentrations as a function of time.

Table 3. Average source contributions derived from the PMF modeling.

Source	Fine PM samples ($\mu\text{g m}^{-3}$)							
	2001–2002 ^a		2005–2006 ^b		2007–2009 ^c		2010–2015 ^d	
	Mass	BC	Mass	BC	Mass	BC	Mass	BC
Motor vehicle	7.16	2.50	5.62	0.38	13.1	1.33	3.19	0.15
Brick kiln	2.23	1.37	11.1	4.14	5.63	1.53	14.1	3.93
Metal smelters	1.87	0.00	1.94	0.53	-	-	-	-
Sea salt	0.19	0.00	0.60	0.00	2.06	0.96	1.75	0.14
Two Stroke/Zn	1.75	1.11	1.94	1.07	1.43	0.87	1.83	0.22
Soil dust	1.92	0.0	2.74	0.18	4.14	0.35	3.59	0.15
Road dust	3.63	1.63	5.14	1.09	4.09	1.00	1.51	0.10
Compressed Natural Gas	-	-	-	-	2.30	0.03	-	-
Fugitive Pb	-	-	-	-	-	-	2.54	0.61
<i>Reconstructed Mass</i>	18.7	6.61	29.1	7.38	32.6	5.67	28.5	5.30
<i>Measured Mass</i>	22.1	7.90	30.5	9.23	36.0	8.26	30.6	6.93

^aBegum *et al.*, 2004.

^bBegum *et al.*, 2011b.

^cBegum *et al.*, 2013.

^dPresent study.

source apportionment results from the 2005–2006 to 2009–2015 data showed reductions of PM and BC from motor vehicle. This result is a positive achievement for the policies adopted by the government.

Banning Leaded Gasoline and its Influence on Air Quality

Lead pollution was identified as a problem in Dhaka in 1980 (Khan *et al.*, 1980) by a research group at the Atomic Energy Centre, Dhaka. A study of the size fractionated ($\text{PM}_{2.5}$ and PM_{10}) airborne particulate matter was conducted during 1993–1995 (Khaliqzaman *et al.*, 1995a, b, 1996, 1999). High airborne Pb concentrations were found originating from cars burning leaded gasoline. These results were reported in national/international press. These reports helped to raise awareness at the national government level and ultimately led to total phase-out lead in gasoline in 1999. After the banning of use of Pb in gasoline, ambient air quality improved. There was a sharp decrease of Pb/BC ratio (Biswas *et al.*, 2003) during that period demonstrating that the primary source of Pb was leaded gasoline.

Unfortunately, there remain problems with airborne lead in Bangladesh. Fig. 6 (bottom) shows significant lead concentrations were still observed throughout the early 2000s. Pb is still being used in an uncontrolled manner in paints and there are fugitive emissions from battery recycling and other industries. It is likely that the major peaks are emissions from small battery reclamation efforts where there are no controls on emissions. These large spikes largely disappeared by 2006 although there were no formal actions taken that might have caused this change.

However, there is also a substantial amount of accumulated lead in dust from earlier deposition. Elevated lead concentrations in the soil reflect this problem (Ahmed *et al.*, 2006). The lead concentrations over the past decade were lower but still exceeded the United States NAAQS value of $0.150 \mu\text{g m}^{-3}$. It is essential to continue lower airborne lead concentrations through the removal of lead in

paints and through the control of emission from suspected industries especially lead based battery industries by regulatory measures.

Brick Production

Brick kilns are important seasonal source of PM and BC. Most production facilities are individual owned and only operated when the ground is dry, primarily from post-monsoon through the winter until the pre-monsoon season). Guttikunda *et al.* (2013) reported that brick manufacturing is the fastest-growing industrial sector in Bangladesh with most bricks being produced in fixed chimney bull trench kilns (FCBTK). About 1000 individual operations in the Dhaka area were estimated to emit 23,300 t of $\text{PM}_{2.5}$, 15,500 t of sulfur dioxide (SO_2), 302,000 t of carbon monoxide (CO), 6,000 t of black carbon, and 1.8 million t of CO_2 . Low-grade coal and agricultural wastes are the primary energy source although the Bangladesh government has now banned the high sulfur coal that had been commonly used until 2014. The Bangladesh Government is trying to reduce the BC emission from brick production sector by adopting greener technologies. As part of a World Bank CASE project, demonstrations of zig-zag and vertical shaft combustion kiln designs were performed showing better fuel economy and lower PM emissions per unit production. Technically, all the FCBTK operations have been banned, but the costs of transformation of the kilns to the newer and cleaner technologies has been difficult for the small operators to afford and the need for bricks has allowed them to continue to operate. Appropriate financing mechanisms could help move this industry toward production using better kiln designs that use less fuel and produce less air pollution.

Transboundary Impacts

South Asia includes the Indian subcontinent (India, Pakistan, Bangladesh, Nepal, and Bhutan), Sri Lanka, and the Maldives. It is densely populated and largely rural.

This region includes five mega cities with populations at or above 10 million: Calcutta, Mumbai, Delhi, Dhaka, and Karachi. These cities are noted for their heavy traffic congestion and related vehicular pollution particularly emissions from diesel/petrol vehicles although there have been efforts to reduce the use of heavy-duty diesels and two-stroke vehicles. CNG has been introduced as an alternative fuel in some locations. However, transport fuel quality remains a serious issue with most diesel fuel having high sulfur content relative to most developed countries.

India relies heavily on coal for electricity generation. Most Indian coals have sulfur content around 0.5% (Chandra and Chandra, 2004). However, it has a relatively low calorific value (~ 4000 kcal kg⁻¹) and high ash contents. The coal mining area of Dhanbad produces substantial particulate pollution from long burning coal mine fires including BC (Singh *et al.*, 2018). Bangladesh generates electricity primarily with natural gas. Pakistan uses oil and natural gas. Nepal depends primarily on biomass fuels. There is substantial use of biomass fuels in India, Nepal, and Bangladesh for cooking and residential heating particularly in rural areas. There is also substantial agricultural waste burning across the Indo-Gangetic Plain (Tiwari *et al.*, 2015).

Begum *et al.* (2011c, 2013) and Ommi *et al.* (2017) shows the potential areas for PM and BC sources in Pakistan, Bangladesh, India, Nepal, and Sri Lanka. Begum *et al.* (2013) found that air masses travel through Iran, Afghanistan, and Pakistan. These Western Disturbances are transported across India to Bangladesh. They bring enough moisture following periods of widespread rain to support thick fog formation (Bisht *et al.*, 2016). There is clearly substantial transport of particulate pollution from northern and northeastern India (see Figs. 7 and 8 in Begum *et al.*, 2013).

Ommi *et al.* (2017) reported the transport of biomass burning aerosol from Pakistan, northern India, and Nepal affected sites in Bangladesh including Dhaka. Fires in northeastern India and Nepal were particularly important with respect to number and intensity of open burning fires (see Figs. 3 to 5 in Ommi *et al.*, 2017) and their resulting impact on air quality in Bangladesh.

CONCLUSIONS

PM concentrations in Dhaka have been measured continuously since December 1996. The Government of Bangladesh has implemented many policies to improve the air quality in Dhaka. Among them, two policies, banning of leaded-gasoline and banning of two-stroke engines, were completely implemented and had measurable effects in improving air quality. A third policy to encourage green technology for brick making is in process. As a result, although there has been substantial economic development and resulting increases in the number of vehicles on the road, PM and BC concentrations have not increased. However, the PM concentrations are still well above health-based guidelines, and further work is needed to achieve good air quality in Dhaka in the near future. Additional policy actions could include cleaning the roads, covering construction

materials, and preventing construction materials from getting onto roadways. Such actions could reduce the high soil contribution ($\sim 20\%$) to PM_{2.5}. Additionally, the brick industry needs to implement improved combustion technologies. If natural gas can be made available to this industry, then emissions could be substantially reduced.

SUPPLEMENTARY MATERIAL

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

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