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Assessment of trends and present ambient concentrations of $PM_{2.2}$ and PM_{10} in Dhaka, Bangladesh

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Abstract The present air quality has been studied at two air quality monitoring stations in Dhaka, the capital of Bangladesh. One site at the Farm Gate area is a particulate matter (PM) hot spot (HSD) with very high pollutant concentrations because of its proximity to major roadways. The other site is in a semi-residential area (SR) located at the Atomic Energy Centre, Dhaka Campus with relatively less traffic. The samples were collected using a 'Gent' stacked filter unit in two fractions of 0–2.2 and 10–2.2 μm sizes. Samples of fine ($PM_{2.2}$) and coarse ($PM_{10-2.2}$) airborne particulate matter collected between 2000 and 2005 were studied. It has been observed that fine particulate matter concentrations at the HSD have decreased from over this period to less than half of the initial value even with an increasing number of vehicles. This decrease is likely the result of governmental policy interventions such as the requirement of vehicle maintenance, training of repair workers, and phase-wise removal of two-stroke three wheelers from the roads in Dhaka with a complete ban of their commercial use beginning on January 1, 2003. Other policy interventions were banning of old buses and trucks from operating in Dhaka, promotion of the compressed natural gas, introduction of pollution control devices on vehicles, control of emissions from industries, etc. It was found that both local (mostly from vehicular emissions and seasonal brick kilns) are responsible for the high $PM_{2.2}$ and

black carbon concentrations in Dhaka. $PM_{2.2}$, $PM_{10-2.2}$, and black carbon concentration levels depend on the season, wind direction, and wind speed. $PM_{10-2.2}$ has not been the focus of policy decisions, and the decrease in concentrations has been much smaller than were observed for the $PM_{2.2}$. There is also some indication of the role of transport of $PM_{2.2}$ from regional sources.

Keywords Particulate matter · Black carbon · Hotspot · Semi-residential area · Bangladesh · Regulatory policy

Introduction

Among the suite of air pollutants, particulate matter (PM) is thought to be the most important pollutant with respect to health effects and reduced urban visibility. The important sources of PM in Dhaka are diesel-powered vehicles, two-stroke engine gasoline vehicles, and brick kilns (Salam et al. 2003; Begum et al. 2004, 2005a, 2006a). These studies have suggested that motorized transport vehicles are the single largest contributor of air pollution in Dhaka, Bangladesh. The annual growth in the number of motorized vehicles has ranged from about 7% to 16% for the last 10 years. This rapid rise in vehicle numbers has exacerbated the air pollution in Dhaka to rapidly worsen even with a major policy intervention in which the use of two-stroke, three-wheeled vehicles were phased out of operation, older vehicles were retired from service, and mechanics training programs were initiated to improve vehicle maintenance. Particulate emissions depend primarily on the engine design, fuel loss due to overfueling, overloading, engines being underpowered and poorly maintained, lubricant oil consumption, and high sulfur content in the fuel. If the vehicle design and maintenance problems of the engines are

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addressed, then particulate emission depends largely on the sulfur content.

Black carbon (or light absorbing carbon) is one of the primary emissions of diesel and other vehicles particularly when they are poorly maintained. There is greatly increased interest in the concentrations of urban black carbon (BC) both because of the likelihood of human health effects that are ascribed to vehicular emissions and the potential effect of BC on climate (Ramanathan and Carmichael 2008).

In order to reduce pollutant concentrations in the atmosphere, pollution sources must be identified, emission estimates made, and effective management strategies developed. There are several receptor models that have been developed to locate pollutant sources that combine meteorology with the measured chemical compositions so that the probable locations of emission sources can be found. The directionality of local-scale sources can be identified by combining measurements of both wind direction and airborne aerosol properties in a conditional probability function analysis (Kim and Hopke 2004).

Regional transport of material from distance sources can also be examined using methods that combine estimates of the motion of the air backward in time with concentrations measured at a sampling site. Such models include residence time analysis (RTA) (Poirot and Wishinshi 1986; Poirot et al. 2001), quantitative transport bias analysis (QTBA) (Keeler and Samson 1989), potential source contribution function analysis (PSCF) (Ashbaugh et al. 1985; Cheng et al. 1993; Polissar et al. 2001), concentration weighted field (CWF) (Seibert et al. 1994), and residence time weighted concentration (RTWC) (Stohl 1996). In this study, the PSCF has been used to asses the impact of regional $PM_{2.2}$ and BC sources. It has been successfully applied in a number of studies (e.g., Ashbaugh et al. 1985; Begum et al. 2005b; Hopke et al. 1995; Biegalski and Hopke 2004).

The main objective of this study was to assess the present ambient air quality, particularly the PM in Dhaka after the Government policy intervention, and to identify possible local and distant PM source locations of the atmospheric aerosol by combining air parcel back trajectories with the particle data.

Material and methods

Sampling

Sampling was performed at two sites in Dhaka using a 'Gent' stacked filter sampler (Hopke et al. 1997) capable of collecting air particulate samples in coarse (10–2.2 μm) and fine (2.2 μm) size fractions. Figure 1 shows the location of two sampling sites and the meteorological station in Dhaka. The hot spot site in Dhaka (HSD) is a high traffic area located at Farm Gate, adjacent to the intersection of several

main roads typically carrying high volumes of traffic (latitude, 23.76° N; longitude, 90.39° E). The sampler was placed on the flat roof of the guardhouse of the Bangladesh Agricultural Research Council. The roof height was 3 m above the ground and the intake nozzle of the sampler was located 1.8 m above the roof. The intake was about 5 m away from the roadside. This site was operated from 2000 until March 2006.

The other sampler was placed in a semi-residential area (SR) area of Dhaka (latitude, 23.77° N; longitude, 90.38° E). 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. This site has been operated since the mid-1990s and continues to be operated.

In this study, samples were collected only on work days. 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 μm pores for the coarse fraction samples and 0.4 μm pores for the fine fraction samples. The filters were equilibrated for 24 h, weighed in an air-conditioned room (approximate temperature of 22°C and relative humidity of 50%), and stored in airtight Petri slides. After sampling, the sample holder (stack filter unit) was returned to the AECD Laboratory for recovery of the filters, and the samples were equilibrated under the same conditions. The post-sampling weighing of the samples was usually completed within 1 month of the sampling date. Comparison of this sampling method with an Airmatrics MiniVol sampler shows that the GENT sampler has comparable sampling efficiency (Begum and Biswas 2005).

Twenty-four-hour representative samples were collected at both sites twice a week on weekday only. About 100 samples (each sample comprises one fine and one coarse) were collected every year from each of the sampling station. The effective sampling time was varied between 6 and 20 h (depending on seasons) distributed uniformly over 24 h a day to avoid filter clogging and so that the flow rate remains within the prescribed limits of the sampler. This ensured proper size fractionation and collection efficiency. Inter-comparison of GENT data with continuous 24-h Airmetrics MiniVol data by collocated sampling suggested (Begum and Biswas 2005) that the data generated using such time-sliced sampling procedure provide reasonably accurate average PM mass data.

PM mass and BC determination

The masses of the coarse and fine fraction samples were determined by weighing the filters before and after the ex-

Fig. 1 Map of Dhaka, Bangladesh showing the locations of the two sampling sites
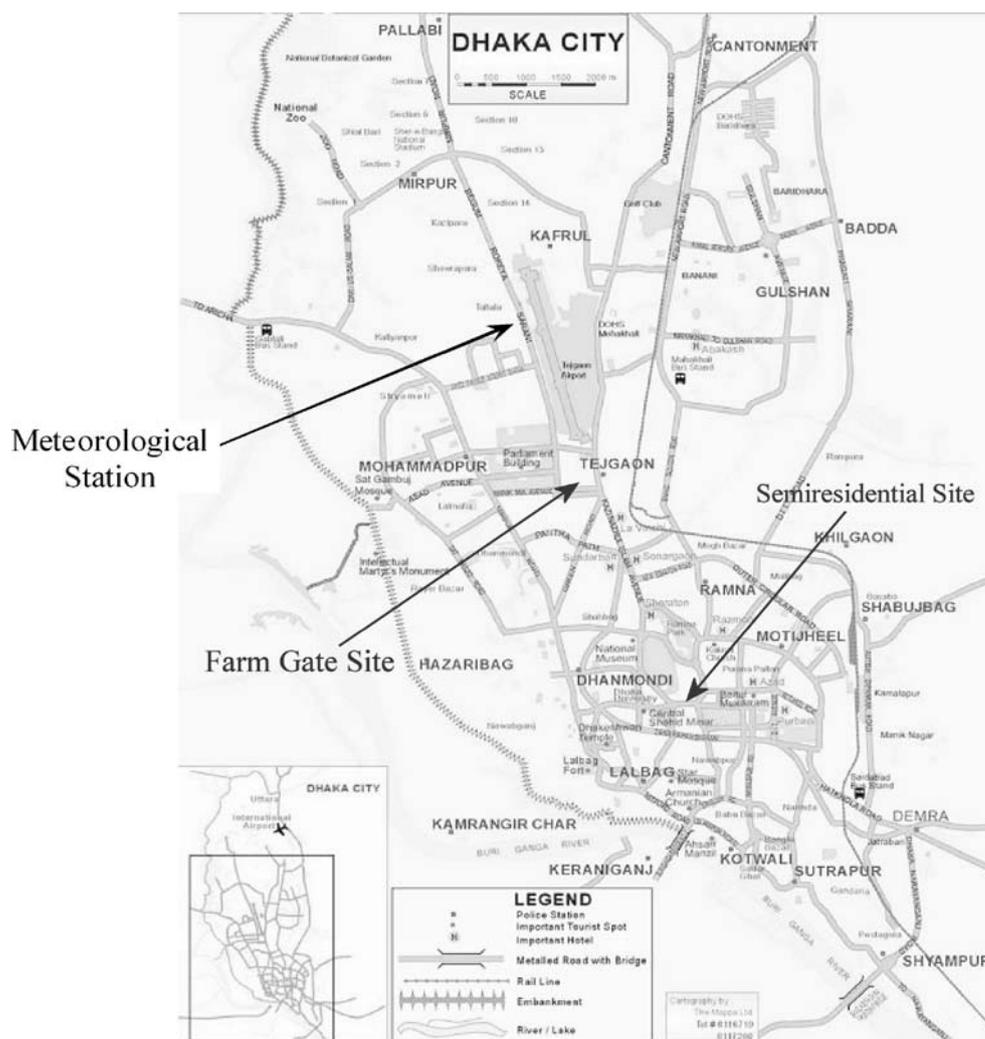
posure. A Po-210 (alpha emitter) electrostatic charge eliminator (STATICMASTER) was used to eliminate the static charge accumulated on the filters before each weighing.

The concentration of BC in the fine fraction of the samples is determined by reflectance measurement using an EEL Smoke Stain Reflectometer. Secondary standards of known black carbon concentrations are used to calibrate the reflectometer (Biswas et al. 2003).

Trajectory ensemble methods

The NOAA hybrid single particle Lagrangian integrated trajectory (HYSPLIT 4) model (Draxler and Rolph 2003) was used to calculate the air mass backward trajectories for those days when fine particles were sampled at both sites. The vertically mixed model starting at 1,000 m above the ground level was used to calculate the 5-day backward trajectories arriving at the receptor site producing 120 endpoints per sample. This height was chosen to diminish the effects of surface friction and to represent winds in the lower boundary layer. Samples were generally collected twice a week. The geophysical region covered by the trajectories was divided into 2,160 grid cells of 1° × 1° latitude and longitude so that there are approximately 25,161 endpoints/2,160 cells or 12 trajectory endpoints per cell in average.

The error associated with the trajectory segment increases as the distance from the receptor site increases. In this trajectory approach, the method looks at the collective properties of a large number of endpoints. So if the errors are randomly distributed in the trajectory endpoint locations, then a sufficient number of endpoints were distributed over the region of interest. In this case, the PSCF values will approach the true values. Thus, the PSCF model provides a means to map the source potentials of geographical areas. It does not apportion the contribution of the identified source area to the measured receptor data.
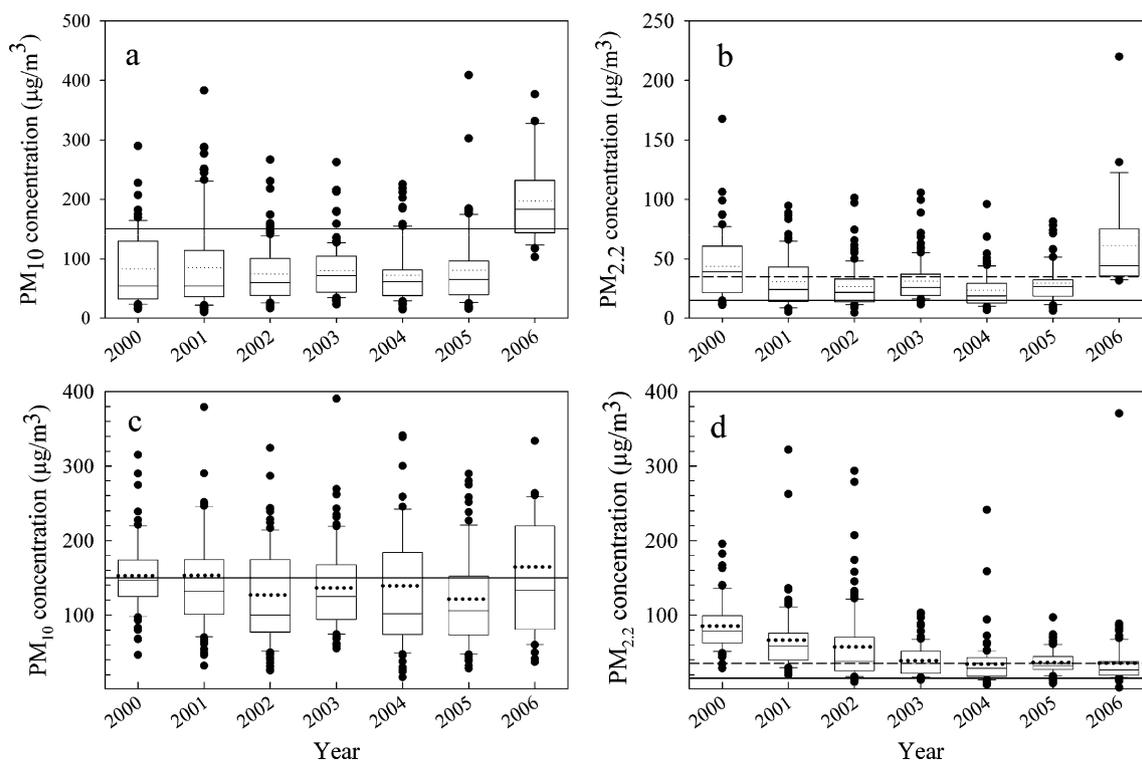
Air parcel backward trajectories were related to the composition of collected material by matching the time of

arrival of each trajectory at the receptor site. The movement of an air parcel is described as a series of segment endpoints defined by their latitude and longitude. The backward trajectories were calculated for each sample collected during the period from May 2001 to March 2005. PSCF values for each grid cell were calculated by counting the trajectory segment endpoints that terminate within the grid cells. The number of endpoints that fall in the ij^{th} cell is $n(i,j)$. The number of endpoints for the same cell when the corresponding samples show concentrations higher than an arbitrarily criterion value is defined to be $m(i,j)$. The PSCF value for the ij^{th} cell is defined as:

$$PSCF(i,j) = m(i,j)/n(i,j). \tag{1}$$

In the PSCF analysis, it is likely that the small values of n_{ij} produce high PSCF values with high uncertainties. In order to minimize this artifact, an empirical weight function $W(n_{ij})$ proposed by Zeng and Hopke (1989) was applied when the number of the endpoints per particular cell was less than about three times the average values of the endpoints per cell.

$$W(n_{ij}) = \begin{cases} 1.0 & 36 < n_{ij} \\ 0.7 & 12 < n_{ij} \le 36 \\ 0.4 & 3 < n_{ij} \le 12 \\ 0.1 & n_{ij} \le 3 \end{cases}$$

Result and discussion

Meteorological conditions

In Bangladesh, the climate is characterized by high temperatures, high humidity most of the year, and distinctly marked seasonal variations in precipitation. According to meteorological conditions, 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 season is characterized by dry soil conditions, low relative humidity, scanty rainfall, and low northwesterly prevailing winds. The rainfall and wind speed become moderately strong and relative humidity increases in the pre-monsoon season when prevailing southwesterly (marine). During monsoon season, the wind speed further increases and the air mass is purely marine in nature. In the post-monsoon season, the rainfall and relative humidity decreases, so as the wind speed. The direction starts shifting back northeasterly. The meteorological data used in this study were obtained from a local meteorological station located about 2 and 5 km north of the HSD and SR sites, respectively.

Particulate matter mass and black carbon concentrations

The 24-h average $PM_{2.2}$ and PM_{10} mass fraction results for the SR sites are shown in Fig. 2a,b as yearly box and

Fig. 2 Box and whisker plots for PM_{10} and $PM_{2.2}$ for the SR site (**a** and **b**, respectively) and the HSD site (**c** and **d**, respectively)

whisker plots. Analogous plots for the HSD site are shown in Fig. 2c,d. In each case, the box represents 25% to 75% of the distributions of the yearly $PM_{2.2}$ and PM_{10} concentrations. The horizontal solid line in the box indicates the median, and the dotted line denotes the mean of the distribution for the year. The points lying outside the range defined by the whiskers (extreme events) are plotted as outlier dots. The lines in the $PM_{2.2}$ plots show the US National Ambient Air Quality Standard values of 15 $\mu g/m^3$ (annual average) and 35 $\mu g/m^3$ (24-h) standards. The lines in the PM_{10} plots show the 150 $\mu g/m^3$ 24-h standard. Figure 3 provides the box and whisker plots for the BC in the $PM_{2.2}$ samples for the two sites.

The arithmetic and geometric mean values of mass concentrations for $PM_{2.2}$ and PM_{10} and $PM_{2.2}$ BC in the samples collected from two sites are given in Table 1. The year-by-year average values for PM_{10}, $PM_{2.2}$, and BC mass concentrations are also presented in Table 1 along with the average $PM_{2.2}/PM_{10}$ and $BC/PM_{2.2}$ ratios.

It can be seen that the mean values are much higher than the 2006 USEPA standards as well as the Bangladesh national air quality standard for $PM_{2.5}$. The PM_{10} mass concentrations are also much higher than the WHO annual average guideline value of 20 $\mu g/m^3$ and a 24-h mean of 50 $\mu g/m^3$. The more detailed time series of PM concentration are plotted in Fig. 4.

At the semi-residential site, the PM_{10} and $PM_{2.2}$ mass concentrations decreased in 2002 and apparently remained relatively constant during the following several years. During this period, various governmental programs were put in place to help reduce the level of airborne PM. These included increased training for motor vehicle mechanics and removal of very old vehicles (>20 years) from the roads. In 2002, efforts began to remove two-stroke vehicles to reduce emissions. In 2003, the commercial two-stroke vehicles were banned and replaced with compressed natural gas (CNG) or four-stroke engines (Begum et al. 2006b). However, there was a sharp rise in both PM concentrations in 2006 (Fig. 2). However, the $BC/PM_{2.2}$ ratio remains relatively constant (Table 1). It was concluded that the increased PM concentration is mainly due to the construction of a building adjacent to the sampling site. From source apportionment studies (Begum et al. 2004, 2005a), it was observed that vehicles normally produce about 50% of fine particles ($PM_{2.2}$ particles). The coarse particles ($PM_{10–2.2}$ particles) mainly originate from mechanical processes (Begum et al. 2006a).

Figure 5 shows the frequency distribution of the daily $PM_{2.2}/PM_{10}$ mass ratios at the two sites during the sampling period. The maxima were found to be around 0.4 both in semi-residential and hot spot areas. This result indicates that for the majority of days, about 40% of the PM mass concentrations are fine particles with aerodynamic diameter less than 2.2 μm that are mainly of anthropogenic and urban activities. 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 contributes significantly to these emissions. Because of the proximity of major roadways in the hot spot 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, and in particular resuspension, depend not only on the vehicle frequency but also on the condition of the roadway (e.g., clean/dirty, wet/dry). It is seen from Table 1 that both the PM_{10} and $PM_{2.2}$ mass concentrations decreased at the hot spot site, but the decreasing trend in $PM_{2.2}/PM_{10}$ suggests that the coarse fraction in the PM decreased less than the $PM_{2.2}$. Given the focus of the control actions on vehicle emissions, the greater effect on $PM_{2.2}$ is what was expected. Again, an increase in the PM_{10} concentration can be seen in 2006 at the HSD site, but not to the same extent as at the SR site.

The population growth in Dhaka is more than 7% per year, while the economic growth is about 6% and vehicular growth is more than 10%. The number of vehicles of
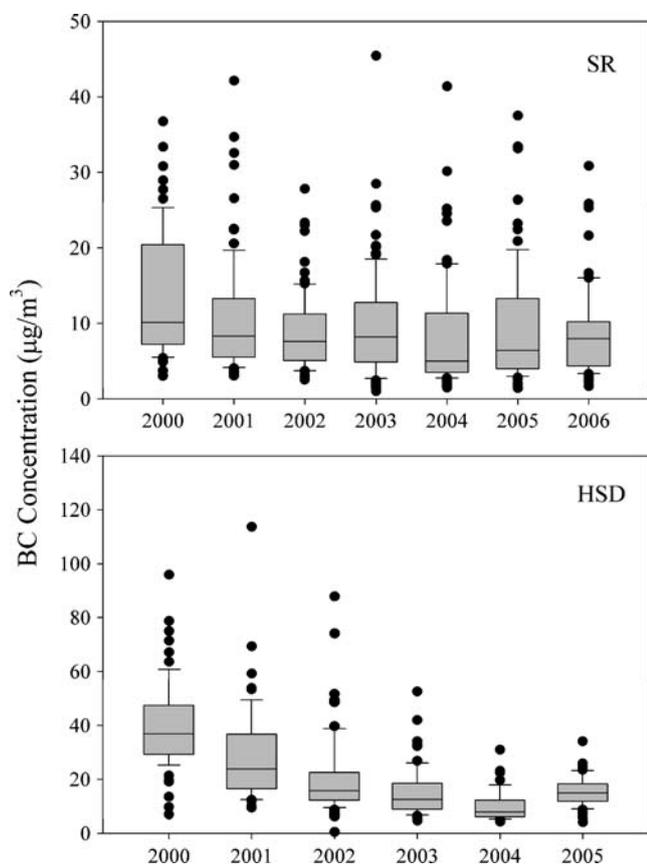
Fig. 3 Box and whisker plots for BC in $PM_{2.2}$ for the SR site (*top*) and the HSD site (*bottom*)

Table 1 Average air particulate matter mass concentration (μg/m³) and PM$_{2.2}$/PM$_{10}$ ratio over the collection period at the hot spot and semi-residential sites in Dhaka

Year	HSD					SR				
	PM$_{10}$	PM$_{2.2}$	BC	PM$_{2.2}$/PM$_{10}$	BC/PM2.2	PM$_{10}$	BC	PM$_{2.2}$	PM$_{2.2}$/PM$_{10}$	BC/PM2.2
2000–2001	170±97.9	90.2±44.9	39.5±17.3	0.53	0.44	110±82.1	15.6±8.90	48.4±27.4	0.44	0.32
2001–2002	146±65.9	66.4±44.2	26.9±13.3	0.45	0.41	70.9±49.5	8.68±4.18	25.6±15.7	0.36	0.34
2002–2003	124±66.6	46.4±32.4	17.8±9.73	0.38	0.38	74.3±46.9	9.32±6.50	29.0±20.5	0.39	0.32
2003–2004	136±56.1	35.7±18.0	13.9±7.46	0.26	0.39	80.6±47.1	9.35±6.73	28.0±14.3	0.35	0.33
2004–2005	131±113	34.8±30.7	10.2±4.74	0.27	0.29	55.6±26.1	6.51±5.47	20.9±11.2	0.38	0.31
2005–2006	140±114	40.8±40.7	18.3±6.99	0.29	0.45	112±86.0	11.1±7.72	37.7±29.8	0.34	0.29

various types being added to the roads of Dhaka on a yearly basis is shown in Fig. 6. There have also been changes in the nature of the vehicles, including the reduction in new two-stroke vehicles, conversion of buses to compressed natural gas, and retirement of old vehicles.

There has been even higher growth in the industrial sector. There are now about 300 mini-steel mills (i.e., with capacity of 50–100,000tons/year) in Bangladesh with a good fraction in Dhaka suburbs. About 20% of these facilities have highly polluting melt shops. Similarly, the building boom has lead to setting up of additional brick kilns. The brick kiln cluster (coal-fired) in north Dhaka is about 550 strong. Increase in services for the growing economy is a major cause for increased air pollution. Thus, the relatively limited rise in PM concentrations in both size fractions indicates that the control actions have helped to balance the increases in pollution that would have been

anticipated to parallel the growth in population, economic activity, and vehicles.
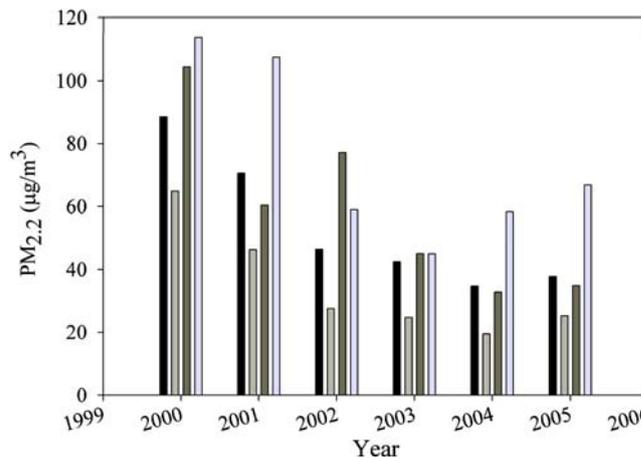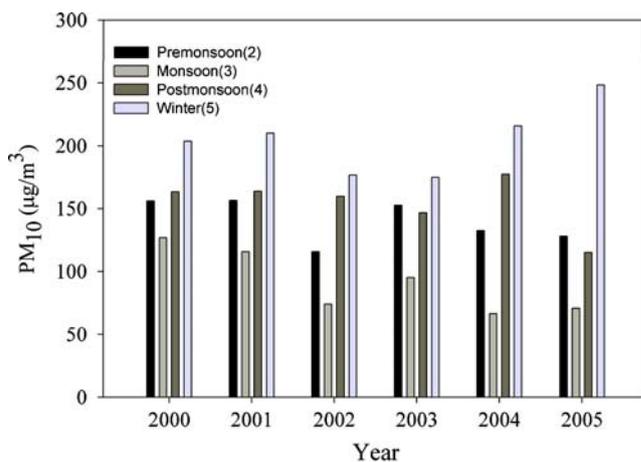
Seasonal variations of PM$_{10}$ and PM$_{2.2}$

Figures 7 and 8 show the variation of PM$_{2.2}$ and PM$_{10}$ mass concentrations in each different season at the SR and HSD sampling sites, respectively. It can be seen from these figures that for both locations, a characteristic seasonal variation is observed for the PM$_{10}$ as well as for the fine particles, with elevated concentrations during the winter. The reasons for the high peaks during the winter are not only caused by seasonal fluctuations of the emissions but also by meteorological effects. During the wintertime, the wind comes mainly from the north and northwest directions.

The major source of PM$_{2.2}$ in Dhaka is motor vehicle and brick kiln emissions (Begum et al. 2004, 2005a). The largest traffic corridors in the city extend toward the north and south, and two such corridors were situated to the west of the sampling sites. A number of brick fields that use both coal and wood as main fuels and operate only in winter due to meteorological condition have grown up around Dhaka, especially on the northwest and southeast side of the city,
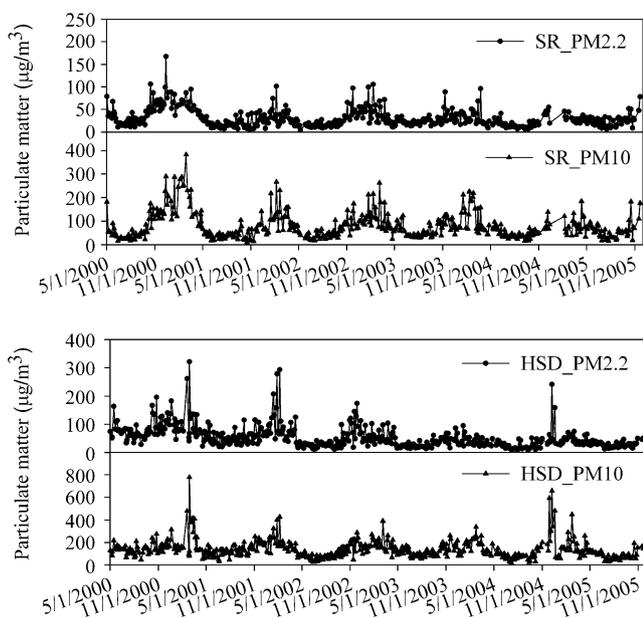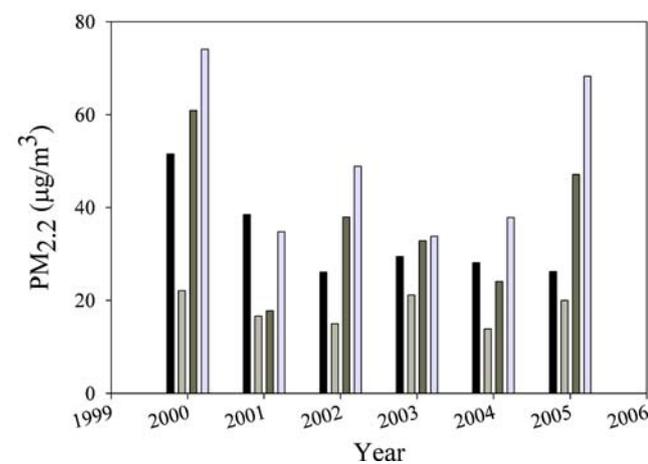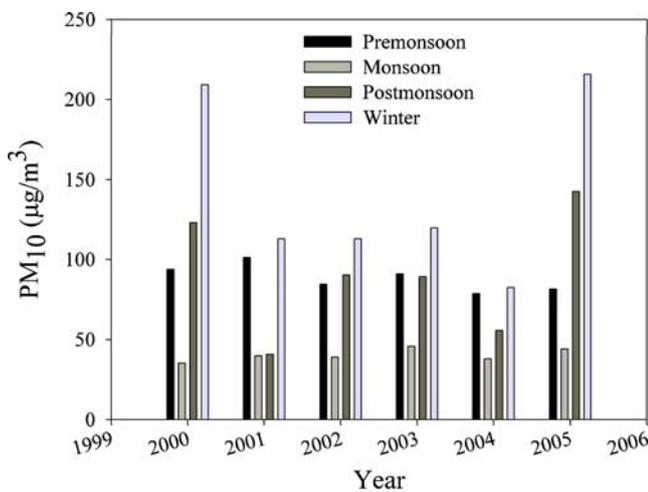

Fig. 4 Time series plots of PM$_{10}$ and PM$_{2.2}$ for the SR site (*top*) and for the HSD site (*bottom*)
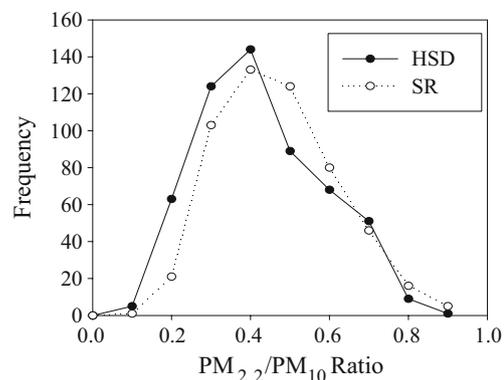
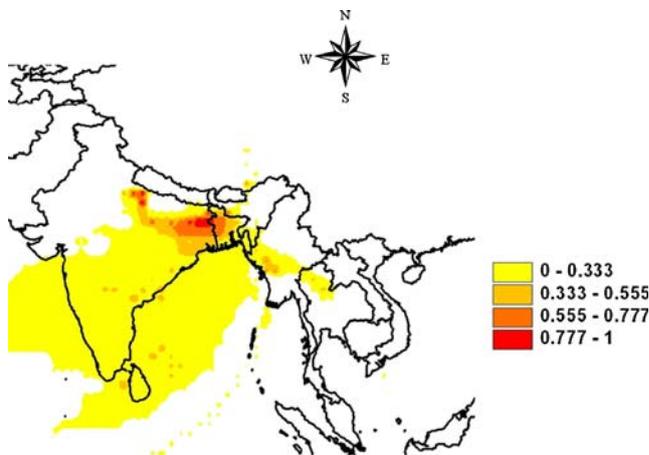**Fig. 5** Frequency distributions of the PM$_{2.2}$/PM$_{10}$ in the samples from the two sites
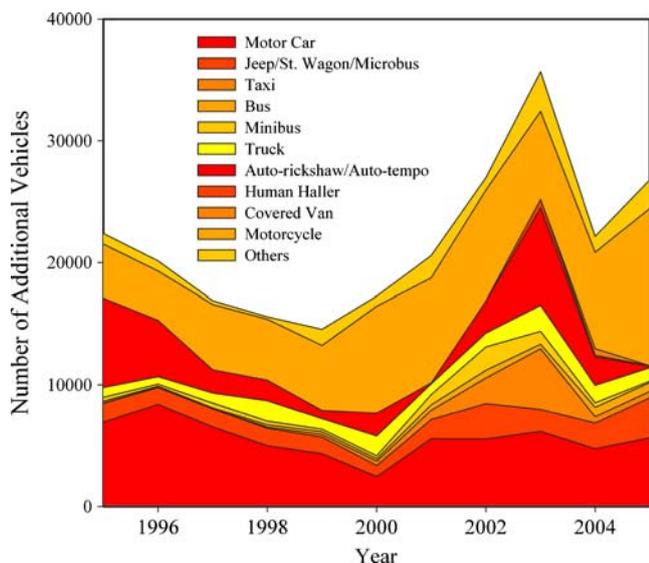
Fig. 6 Year-by-year registration of vehicles in Dhaka City (Source: Bangladesh Road Transport Authority)

Fig. 8 Seasonal patterns of PM_{10} and $PM_{2.2}$ for the HSD site

because bricks are the main construction material in the city. Therefore, emissions from various kinds of automobiles and the brick kilns are believed to be the two major contributors to the severe air pollution in winter in Dhaka. However, it is also useful to explore how much of the particulate matter is transported into the Dhaka region.

Fig. 7 Seasonal patterns of PM_{10} and $PM_{2.2}$ for the SR site

Fig. 9 PSCF plot for $PM_{2.2}$ mass concentrations based on data from both sites
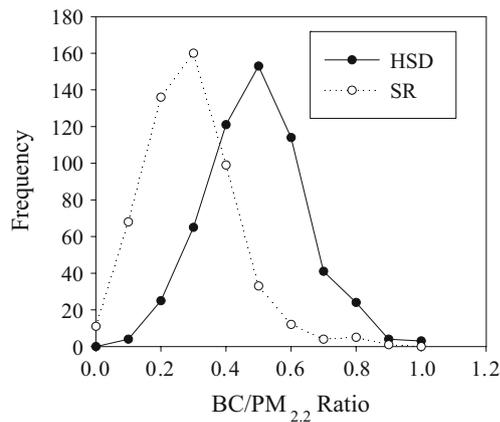
Fig. 10 Frequency distributions of the BC/PM$_{2.2}$ in the samples from the two sites

Transboundary effects

The combined site PSCF plot is shown in Fig. 9. The PSCF results are displayed in the form of a map of the areas of high probability such that the PSCF values are displayed in terms of a color scale. The PSCF map shows some influence of the northwestern part of India on PM$_{2.2}$ concentrations in Dhaka. The results show reasonable agreement with the SO$_2$ source areas in eastern and northern India that are shown in Fig. 1b of Adhikary et al. (2007).

The relationship of PM$_{2.2}$ and black carbon

Figure 10 shows the frequency distribution of the daily BC/PM$_{2.2}$ mass ratios at the two sites during the sampling period. The maxima were found to be around 0.3 and 0.5 for samples collected in the semi-residential and hot spot sites, respectively, which suggests that BC fraction is dominant in the majority of the samples in the hot spot
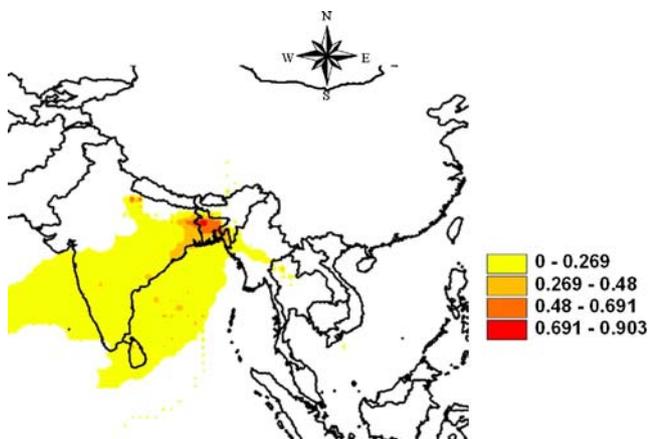
Fig. 11 PSCF plot for BC in PM$_{2.2}$ mass concentrations based on data from both sites

area than that of the semi-residential site due to higher traffic in the hot spot area. Motor vehicle emissions are major source of BC in Dhaka (Begum et al. 2004, 2005a). The concentration of BC is higher in the hot spot area than at the semi-residential area not only due to the proximity of major busy roadways but also more commercial activities where people use diesel power during power failures. On the other hand, there are largest numbers of brick kiln in the northwest direction of the sampling location, which is about 20 km away from the hot spot. These kilns are also BC contributor of the PM$_{2.2}$ mass. BC also exhibits similar characteristic of seasonal variation observed in the fine particles with relatively higher concentrations during the dry season.

Black carbon is a tracer of primary anthropogenic emissions, and its variability reflects changes in source strengths, long-range transport, and atmospheric mixing characteristics. Moreover, the BC concentration observed to be dependent on the wind direction (based on values from CPF calculations), both northwesterly and northeasterly, could be due to both regional or long-range transport (Novakov et al. 2000; Lelieveld et al. 2001; Viidanoja et al. 2002) as well as local source effects. To explore the possibility of long-range transportation of pollutants from fossil-fuel-related sources and biomass burning being substantial sources of BC, it can be seen (Fig. 11) that the area of high probably is in the region around Dhaka, indicating that the BC arises largely from local sources with some possible transport from the rest of Bangladesh and eastern India. Ramanathan and Carmichael (2008) show this area in Fig. 5a of their paper as a region of high biomass burning BC concentrations.

Conclusion

Temporal and spatial pattern analysis of PM data is important for source identification. Moreover, consideration of spatial and temporal scales helps to focus PM management strategies on the effects of concern. Begum et al. (2004, 2005a, 2006b) found that about 40% of the PM$_{10}$ mass in Dhaka is fine particles with aerodynamic diameter less than 2.2 μm that are mainly of anthropogenic origin and predominately from transportation-related sources. To reduce the air pollution caused by vehicular emission, the Government of Bangladesh has undertaken a series of actions. They banned two-stroke three wheelers from Dhaka city and replaced them with four-stroke CNG engine vehicles. In addition, a large number of buses were converted to CNG engines. There have been training programs for vehicle mechanics. Although the numbers of vehicles on the roads in Dhaka are increasing each year, the PM$_{2.2}$ concentrations have not increased linearly since the vehicles are burning

cleaner fuels, older vehicles have been retired, and better trained mechanics are able to better service the vehicles.

The $PM_{10-2.2}$ fractions were not as readily able to be controlled. This fraction contains about 70% soil and road dust particles based on prior source apportionment studies, and efforts have not yet been undertaken to reduce resuspension of road dust. BC has a relatively higher contribution to $PM_{2.2}$ mass during the dry season. There is also observable improvement in the extent of the haze along the traffic corridors of the city and are likely due to significant reduction in PM emissions from the vehicle fleet.

References

Adhikary B, Carmichael GR, Tang Y, Leung LR, Qian Y, Schauer JJ, Stone EA, Ramanathan V, Ramana MV (2007) Characterization of the seasonal cycle of south Asian aerosols: a regional-scale modeling analysis. J Geophys Res 112:D22S22. doi:10.1029/2006JD008143

Ashbaugh LL, Malm WC, Sadeh WZ (1985) A residence time probability analysis of sulfur in the western United States. Atmos Environ 18:783–791. doi:10.1016/0004-6981(84)90262-2

Begum BA, Biswas SK (2005) Comparison of PM collection efficiency of Gent and Airmatrics MiniVol portable air sampler. Nucl Sci Appl I14:79–83

Begum BA, Kim E, Biswas SK, Hopke PK (2004) Investigation of sources of atmospheric aerosol at urban and semi-urban areas in Bangladesh. Atmos Environ 38:3025–3038. doi:10.1016/j.atmosenv.2004.02.042

Begum BA, Biswas SK, Kim E, Hopke PK, Khaliquzzaman M (2005a) Investigation of sources of atmospheric aerosol at a hot spot area in Dhaka, Bangladesh. J Air Waste Manage Assoc 55:227–240

Begum BA, Kim E, Jeong C-H, Lee D-W, Hopke PK (2005b) Evaluation of the potential source contribution function using the 2002 Quebec Forest Fire Episode. Atmos Environ 39:3719–3724

Begum BA, Biswas SK, Hopke PK (2006a) Impact of banning of two-stroke engines on airborne particulate matter concentrations in Dhaka, Bangladesh. J Air Waste Manage Assoc 56:85–89

Begum BA, Biswas SK, Hopke PK (2006b) Temporal variations and spatial distribution of ambient PM2.2 and PM10 concentrations in Dhaka, Bangladesh. Sci Total Environ 358:36–45. doi:10.1016/j.scitotenv.2005.05.031

Biegalski SR, Hopke PK (2004) Total potential source contribution function analysis of trace elements determined in aerosol samples collected near lake Huron. Environ Sci Technol 38:4276–4284. doi:10.1021/es035196s

Biswas SK, Tarafdar SA, Islam A, Khaliquzzaman M, Tervahattu H, Kupiainen K (2003) Impact of unleaded gasoline introduction on the concentration of lead in the air of Dhaka, Bangladesh. J Air Waste Manage Assoc 53:1355–1362

Cheng M-D, Hopke PK, Barrie L, Rippe A, Olson M, Landsberger S (1993) Qualitative determination of source regions of aerosol in Canadian high Arctic. Environ Sci Technol 27:2063–2071. doi:10.1021/es00047a011

Draxler RR, Rolph GD (2003) HYSPLIT 4 (Hybrid single-particle Lagrangian integrated trajectory) model. Access via NOAA ARL READY website

Hopke PK, Barrie LA, Li S-M, Cheng M-D, Li C, Xie Y (1995) Possible sources and preferred pathways for biogenic and non-sea-salt sulfur for the high arctic. J Geophys Res 100(D12):16595–16603. doi:10.1029/95JD01712

Hopke PK, Xie Y, Raunemaa T, Biegalski S, Landsberger S, Maenhaut W, Artaxo P, Cohen D (1997) Characterization of Gent stacked filter unit PM10 sampler. Aerosol Sci Technol 27:726–735. doi:10.1080/02786829708965507

Keeler GJ, Samson J (1989) Spatial representativeness of trace element ratio. Environ Sci Technol 23:1358–1364. doi:10.1021/es00069a005

Kim E, Hopke PK (2004) Comparison between conditional probability function and nonparametric regression for fine particle source directions. Atmos Environ 38:4667–4673. doi:10.1016/j.atmosenv.2004.05.035

Lelieveld J, Crutzen PJ, Ramanathan V, Andreae MO, Brenninkmeijer CAM, Campos T, Cass GR, Dickerson RR, Fischer H, de Laat AT et al (2001) The Indian Ocean experiment: widespread air pollution from South and Southeast Asia. Science 291:1031–1036. doi:10.1126/science.1057103

Novakov T, Andreae MO, Gabriel R, Kirchstetter TW, Mayol-Bracero OL, Ramanathan V (2000) Origin of carbonaceous aerosols over the tropical Indian ocean: biomass burning or fossil fuels. Geophys Res Lett 27:4061–4064. doi:10.1029/2000GL011759

Poirot RL, Wishinshi PR (1986) Visibility, sulfate and air mass history associated with the summertime aerosol in northern Vermont. Atmos Environ 20:1457–1469. doi:10.1016/0004-6981(86)90018-1

Poirot RL, Wishinshi PR, Hopke PK, Polissar AV (2001) Comparative application of multiple receptor methods to identify aerosol sources in northern Vermont. Environ Sci Technol 35:4622–4636. doi:10.1021/es010588p

Polissar AV, Hopke PK, Harris JM (2001) Source regions for atmospheric aerosol measured at Barrow, Alaska. Environ Sci Technol 35:4214–4226. doi:10.1021/es0107529

Ramanathan V, Carmichael G (2008) Global and regional climate changes due to black carbon. Nat Geosci 1:221–227. doi:10.1038/ngeo156

Salam A, Bauer H, Kassin K, Ullah SM, Puxbaum H (2003) Aerosol chemical characteristics of a mega-city in Southeast Asia (Dhaka, Bangladesh). Atmos Environ 37:2517–2528. doi:10.1016/S1352-2310(03)00135-3

Seibert P, Kromp-Kolb H, Baltensperger U, Jost DT, Schwikowshi M, Kasper A, Puxbaum H (1994) Transport and transformation of pollutants in the troposphere. Academic, Den Haag, pp 689–693

Stohl A (1996) Trajectory statistics—a new method to establish source-receptor relationships of air pollutants and its application to the transport of particulate sulfate in Europe. Atmos Environ 30:579–587. doi:10.1016/1352-2310(95)00314-2

Viidanoja J, Sillanpaa M, Laakia J, Kerminen V-M, Hillamo R, Aarnio P, Koskentalo T (2002) Organic and black carbon in PM2.5 and PM10: 1 year of data from an urban site. Atmos Environ 36:3183–3193. doi:10.1016/S1352-2310(02)00205-4

Zeng Y, Hopke PK (1989) A study on the sources of acid precipitation in Ontario, Canada. Atmos Environ 23:1499–1509. doi:10.1016/0004-6981(89)90409-5