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PM_{10}, $PM_{2.5}$ and Black Carbon Concentrations at Urban Environments in Bangladesh

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Executive Summary

As a part of the Bangladesh Air Pollution Studies (BAPS) project, an analysis of PM and BC samples was performed for four cities in Bangladesh. The screening study work fell under Task 3 (Source Apportionment) of the BAPS project.

Four major cities, Rajshahi, Dhaka, Khulna and Chittagong, in Bangladesh have been suffering for many years with severe air pollution particularly by particulate matter (PM). PM samples were collected between September 2010 to July 2012 at four Continuous Air Monitoring Stations (CAMS) located at Farm Gate in Dhaka, Sapura in Rajshahi, Baira in Khulna and a TV station, Khulshi in Chittagong. PM sampling was performed using dichotomous samplers, which collect samples in two sizes: $PM_{2.5}$ and $PM_{2.5-10}$. Samples were collected on 37 mm Teflon filters. These filters were weighed for PM mass, analyzed for Black Carbon (BC) by transmissometry and elements by X-Ray Flourescence (XRF).

Data reveal that the pollution from particulate matter varies greatly with climatic conditions. It was found that the PM and BC concentrations in Rajshahi were higher than the other three cities (Dhaka, Khulna and Chittagong). A major cause might be transboundary transport of pollutants from agricultural burning in upwind regions. This result was surprising given the number of brick kilns and vehicles in Dhaka being the highest of all of these cities. The industrial emissions of PM in Chittagong were also expected to be high. The highest daily $PM_{2.5}$ concentration was 842 $\mu g/m^3$ in Rajshahi and it occurred at a time when long-range pollutant transports were expected to be high.

Contents

Bangladesh Air Pollution Studies (BAPS) PM_{10}, $PM_{2.5}$ and Black Carbon Concentrations at Urban Environments in Bangladesh

1 Introduction

This study is the first preliminary analysis of Particular Matter (PM) and Black Carbon (BC) data under Task 3 of the Bangladesh Air Pollution Studies (BAPS) project. The basis of Task 3 work is outlined in the report *Task 3 (Source Apportionment) Inception Report* prepared by NILU June 2012 [1].

Particulate air pollution is a mixture of particles that vary in number, size, surface area, chemical composition, solubility and origin. Many studies have shown that PM2.5 has significant negative impact on human health [1-3-5]. PM_{10} is derived from suspension and re-suspension of solid particles and contributes greatly to the mass of the total suspended particles in urban environments. Prior work in Dhaka, Bangladesh has shown that fine particles contribute about 60% to the PM10 mass [6]. Subsequent studies have found that 63% of $PM_{2.5}$ is PM_1 [7]. Hence most of the PM_1 particles are in the accumulation mode. It has also found that BC concentration is higher in $PM_{2.5}$. The main sources of $PM_{2.5}$ were identified as motor vehicles, brick kilns, Zn sources, smelters and soil dust [8-9]. Several studies have shown that there is also trans-boundary contribution during the wintertime when wind blows from north and northwest directions [10] during winter.

The Department of Environment (DoE) has been conducting an air quality monitoring program at Continuous Air Monitoring stations (CAMS), in four major cities, namely Rajshahi, Dhaka, Khulna and Chittagong since September 2010, see Table 1. In this paper, data were analyzed from PM samples that were collected from stations in these four different cities using dichotomous samplers to measure $PM_{2.5}$ and $PM_{2.5-10}$. The objectives of this work are to find out the seasonal variation of particulate matters and BC concentrations, distribution of PM in different cities and to investigate the quantitative measurement of transported fine PM in Bangladesh.

Table 1: Description of continuous air monitoring network

City	Location	Lat/Lon	Continuous Monitoring capacity
Dhaka	Farm Gate (CAMS-2)	23.76°N 90.39°E	$PM_{2.5-10}$, $PM_{2.5}$, CO, SO_2, NO_X, O_3, and HC with meteorological parameters.
Chittagong	TV station, Khulshi (CAMS-3)	22.36°N 91.80°E	$PM_{2.5-10}$, $PM_{2.5}$, CO, SO_2, NO_X, O_3, and HC with meteorological parameters.
Rajshahi	Sapura, Rajshahi Cantonment area (CAMS-4)	24.38°N 88.61°E	$PM_{2.5-10}$, $PM_{2.5}$, CO, SO_2, NO_X, O_3, and HC with meteorological parameters.
Khulna	Baira (CAMS-5)	22.48°N 89.53°E	$PM_{2.5-10}$, $PM_{2.5}$, CO, SO_2, NO_X, O_3, and HC with meteorological parameters

2 Methods

2.1 Sampling

Samples were collected on 37 mm diameter Teflon filters using Thermo Andersen dichotomous samplers, which were programmed to sample at 16.7 lpm for proper size fractionation. The samplers in each station were positioned with the intake upward and located in an unobstructed area at least 30 cm from any obstacle to air flow and the sampler inlet was placed at a height of 10 m above ground level. Appropriate QA/QC protocol was followed during sampling and mass measurements by DoE technicians. Quality assurance of the sampling was ensured by using appropriate laboratory and field blanks. The sampling protocol was every third day starting from September 2010 and continuing to July 28, 2012 at essentially all sites. After sampling, the filters were brought to conditioned weighing room of DoE directly from the sampling site for equilibration and PM mass measurement. Care was taken in transporting the exposed filters, so that there should be no PM loss.

2.2 Site description and measurement period

A map of all sampling sites can be found in Figure 1.

Figure 1. Map of sampling locations in Bangladesh

The capital city Dhaka is congested with a large number of motor vehicles on roadways which are very dusty during the dry winter season. Many small factories (especially brick kilns) are also located in and around the city. The CAMS-2 site is at Farmgate in Dhaka (latitude: 23.76°N; longitude: 90.39°E). Farmgate is characterized as a hot spot site due to the proximity of several major roadways, intersections and high volume of vehicles plying through the area [11]. The site is surrounded by a large commercial and residential area. It was found from a previous source apportionment study that the main pollutant sources are road dust, soil dust, sea salt, Zn source, motor vehicle and brick kiln in this site [12].

Chittagong (latitude 22.22°N, longitude 91.47°E) has the largest port in Bangladesh and has heavy traffic, especially the central city area covering about 10 km^2. The main road network in the city runs from the port area northward towards the industrial areas. These roads are also heavily trafficked and dusty during the dry winter season, with persistent traffic jams most of the day. Trucks transporting goods between the port and the industrial areas constitute a significant part of the traffic, and the combination of the hilly nature of the area, the stop and start mode of the congested traffic and the age and heavy loading of most of the trucks causes significant emissions of black diesel smoke. The location of the CAMS-3 is in the Chittagong Television Station Campus at Khulshi, which is on a hilltop about 2.5 km northwest of the Chittagong downtown area and about 100 meters above the surrounding area. There are very few sources within the immediate surrounding area of this CAMS, and it is considered representative of the air pollutant concentrations of the urban background. The major sources indentified in previous studies were biomass burning/brick kiln, soil dust, road dust, Zn source (including two-stroke motorcycles), motor vehicle, CNG vehicle, and sea salt in the Chittagong aerosol [13].

Rajshahi, a metropolitan city, is situated in the northern region of Bangladesh (latitude 24.37°N, longitude 88.70°E) and near the border with India. The location of the CAMS-4 is in Sapura at the Divisional Forest Office. There are few small industries surrounding the sampling site. The climatic conditions are very similar to Dhaka. As there is a low number of industries, apart from brick kilns in Rajshahi city, it has been found that the contribution of biomass burning at this site is highest [14]. This biomass burning contribution may originate from both brick industry, domestic burning/residential combustion (cooking with low grade fuels) or from trans-boundary transport.

Khulna, the third largest city of the country, is situated in the southern region of Bangladesh (latitude 22.48°N, longitude 89.53°E) and near the Bay of Bengal. Being located in a large river delta, it is the second port area of Bangladesh. CAMS-5 is located at Samagic Bonayan Nursery and Training Center in Baira which is about 3 km north of Khulna main town. There are many small factories near the sampling site (both west and south sides), which are producing Touchwood, a special type of fuel, which is made by rice husk and used as fuel for cooking.

211, 185, 145 and 114 pairs of $PM_{2.5-10}$ and $PM_{2.5}$ samples were collected on 37 mm diameter Teflon filters at the Rajshahi, Dhaka, Khulna and Chittagong CAMS, respectively, by Clean Air and Sustainable Environment Project (CASE) project staff at DoE. These samples were collected between September 2010 and July 2012 depending on the cities (Table 2). Quality assurance of the sampling was ensured by CASE/DoE by using appropriate laboratory and field blanks .

2.3 PM mass and BC analysis

PM mass was measured in the laboratory of the DoE. The $PM_{2.5}$ masses were determined by weighing the filters before and after exposure using a microbalance [16]. The filters were equilibrated for 24 hours at a constant humidity of 50% and a constant temperature (22°C) in the balance room before every weighing. A Po-210 (alpha emitter) electrostatic charge eliminator was used to eliminate the static charge accumulated on the filters before each weighing. The difference in weights for each filter was calculated and the mass concentrations for each $PM_{2.5}$ and $PM_{2.5-10}$ samples were determined.

Black carbon (BC) measurements were conducted with a two-wavelength transmissometer (model OT-21, Magee Scientific, Berkeley, CA). The two-wavelength transmissometer measures the optical absorption of the ambient PM sample at 880 nm (BC) and 370 nm (UVBC) [17]. Certain organic aerosol components of wood combustion particles have enhanced optical absorption at 370 nm relative to 880 nm. A calculated variable, Delta-C signal (UVBC(370nm) – BC(880nm), has been suggested as an indicator of wood combustion particles, but is not a direct quantitative measurement of their mass concentrations [18-19].

2.4 Meteorological Conditions

In Bangladesh, the climate is characterized by high temperatures and high humidity for most of the year, with 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) [20]. The winter season is characterized by dry soil conditions, low relative humidity, almost no rainfall, and low north-westerly prevailing winds. The rainfall and wind speeds become moderately strong and relative humidity increases in the pre-monsoon season when the prevailing direction changes to south- westerly (marine). During the 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, as does the wind speed. The wind direction starts shifting back to north- easterly [21]. The dispersion of PM strongly depends on the wind speed and direction [22]. Meteorological data such as wind speed, wind direction, rainfall, humidity, temperature and visibility data according to sampling dates were collected from the Bangladesh Meteorological Department. The Bangladesh Meteorological Department is the authorized Government organization for all meteorological activities in the country. It maintains a network of surface and upper air observatories, radar and satellite stations, agro-meteorological observatories, geomagnetic and seismological observatories and meteorological telecommunication system. The Meteorological Department collects meteorological data at three hours intervals.

2.5 Back Trajectory Calculation

Using models of atmospheric transport, a trajectory model calculates the position of the air being sampled backward in time from the receptor site from various starting times throughout the sampling interval. The trajectories are presented as a sequence of latitude and longitude values for the endpoints of each segment representing each specific time interval being modeled. The vertical motion of air parcels is considered during this model. The NOAA Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT-4) [23] model was used to calculate the air mass backward trajectories for those days when fine particles were sampled.

3 Results

3.1 Daily average value

Figures 2, 3 and 4 show the annual variation of daily averaged PM_{10}, $PM_{2.5}$ and BC concentrations for all 4 sites. From Figures 2 and 3, it can be seen that the 24-hr average PM concentrations followed a systematic cycle throughout the entire monitoring period. During the winter season, the PM concentrations exceeded the Bangladesh National Air Quality Standards (NAAQS) of 150µg/m^3 average for 24 hours from PM_{10} and 65 µg/m^3 average for 24 hours for $PM_{2.5}$ almost every day. The PM concentrations start to increase in November as the dry winter season sets in and decrease in March when the monsoon rainfall starts. In the monsoon season, the daily PM averages became less than the NAAQS, particularly in

August and September. However, during the winter, the day-to-day variations of PM concentrations were higher than during the monsoon period. In addition, Figure 4 shows that BC concentrations are highest in the winter season for all stations, except for Chittagong. Chittagong has a much different seasonal variation that the other stations as BC concentrations are highest in the summer monsoon season. This is because the rainfall in Chittagong is much higher than other cities (Figure 5). As a result, other sources except BC have been washed out due to precipitation and the BC/$PM_{2.5}$ ratio becomes high.

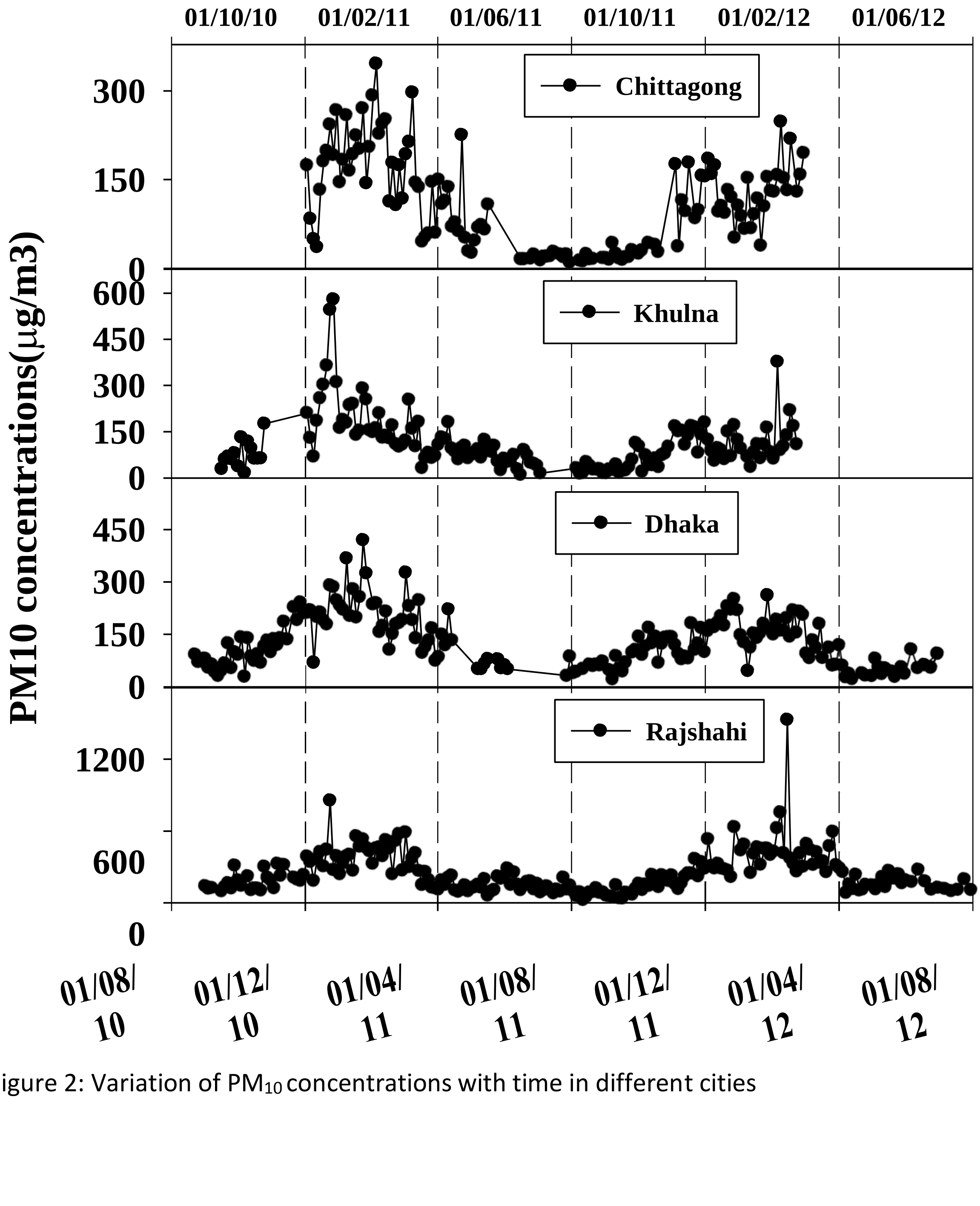

Figure 2: Variation of PM_{10} concentrations with time in different cities

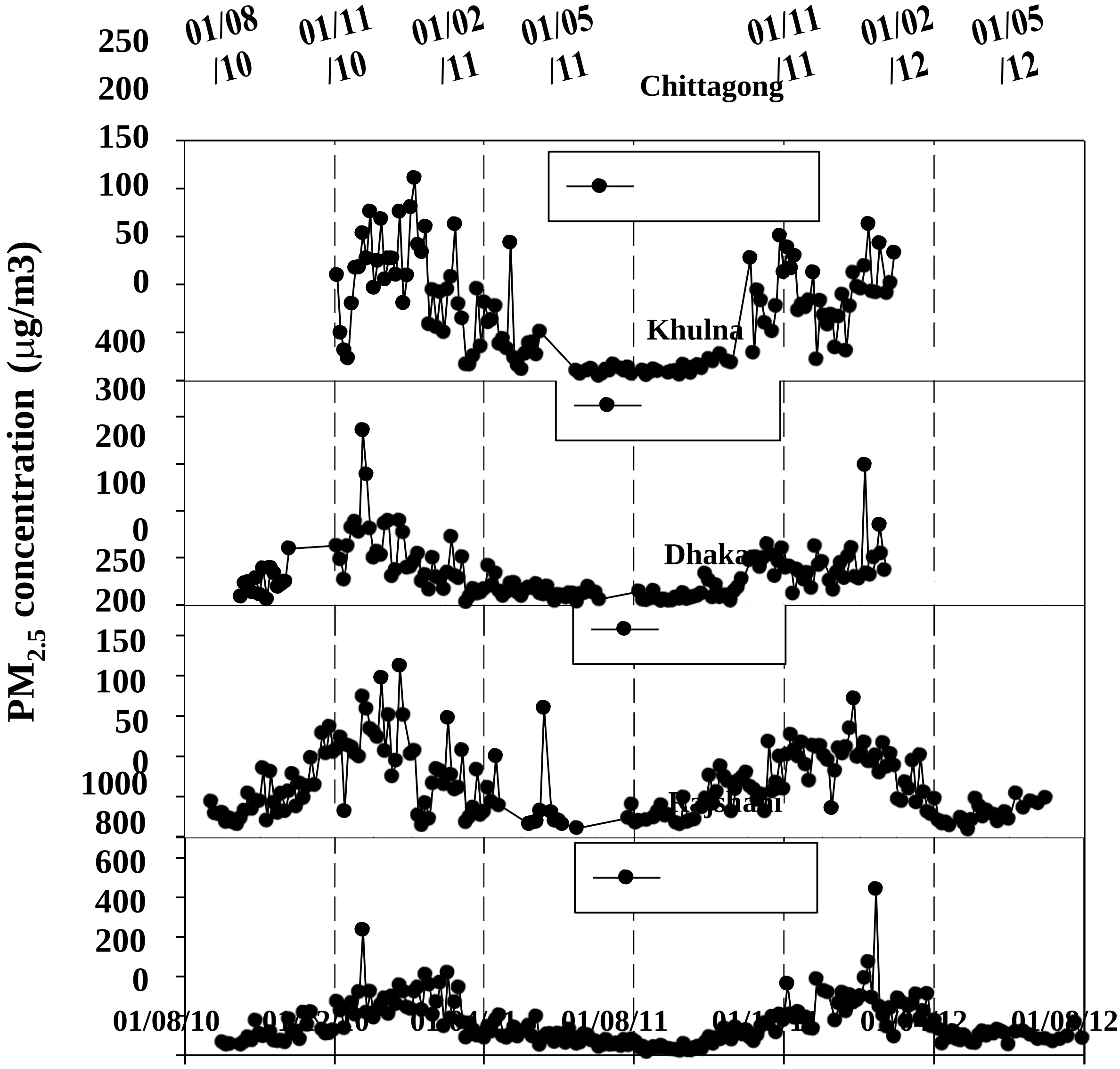

Figure 3: Variation of $PM_{2.5}$ concentrations with time in different cities

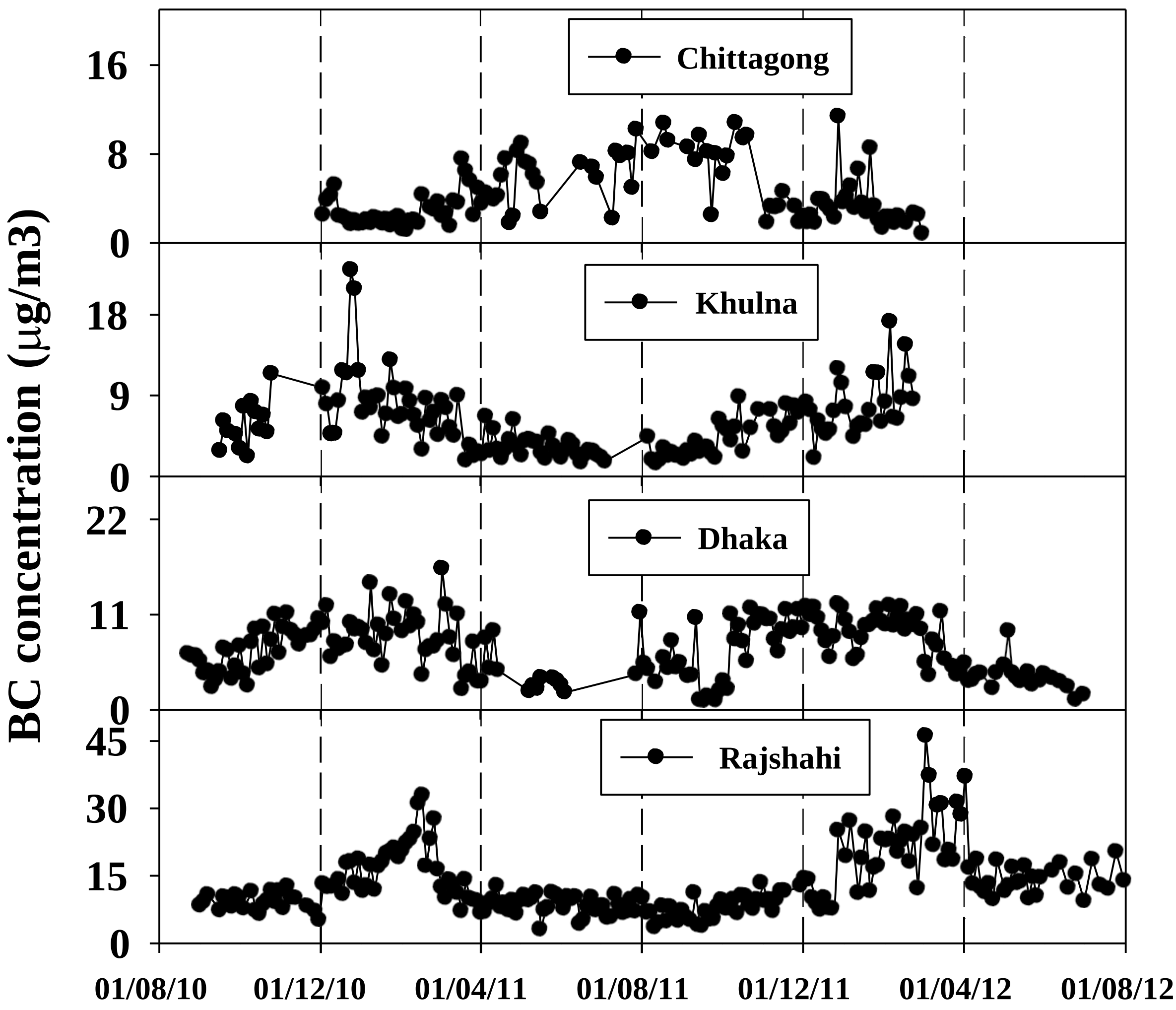

Figure 4: Variation of BC concentrations with time in different cities

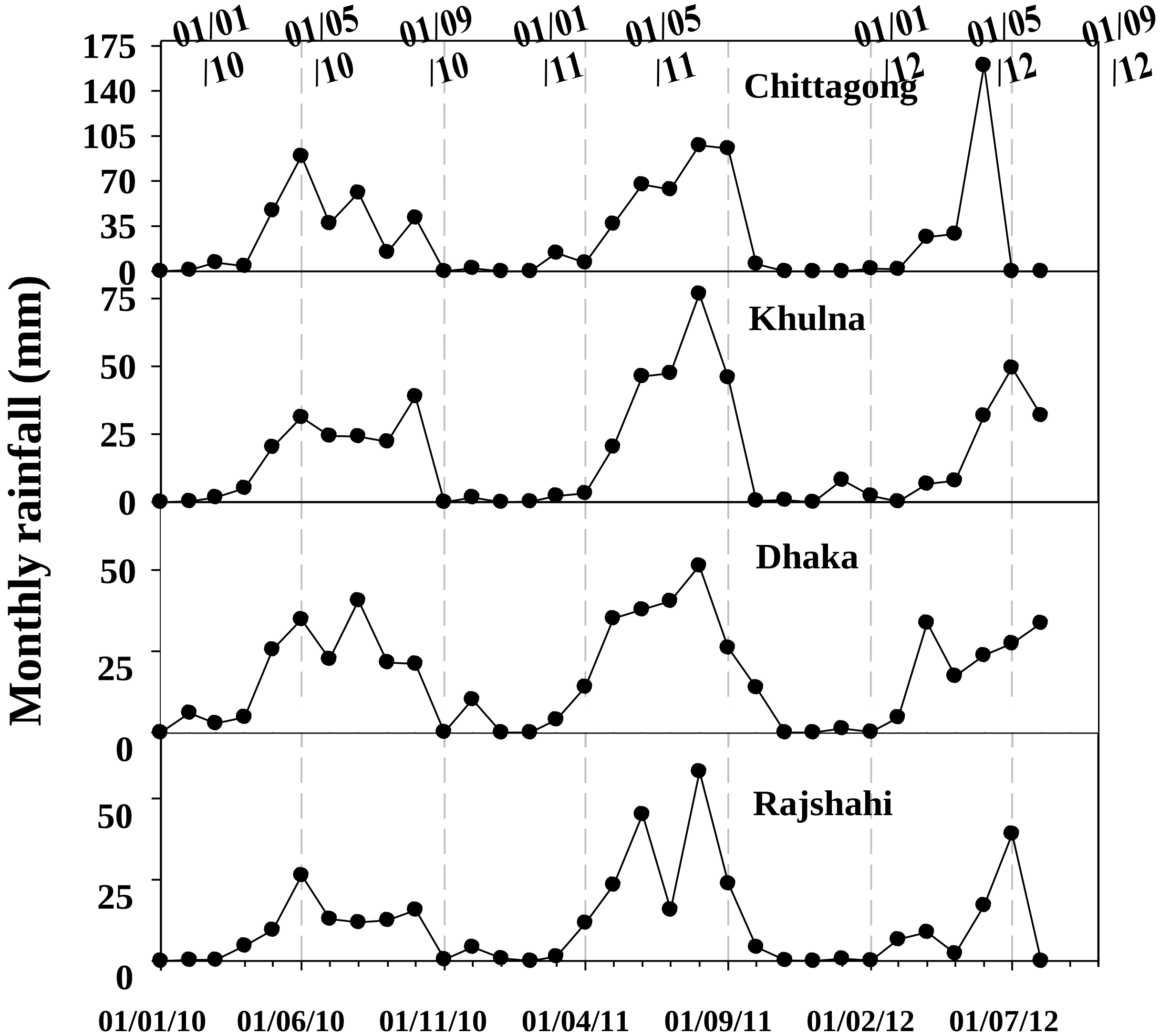

Figure 5: Variation of rainfall (mm) with time in different cities

3.2 Monthly variation and annual average

Figure 6 shows the monthly average PM_{10}, $PM_{2.5}$ and BC concentrations with their standard deviations during the sampling periods in these cities. It can be seen that in case of Rajshahi city, the PM concentrations exceed the annual average standards (PM_{10} = 50 µg/m^3 and $PM_{2.5}$ = 15 µg/m^3) in every month of the year. The other three cities also exceeded the NAAQS standards in winter, and have concentrations near the standard levels from June to August.

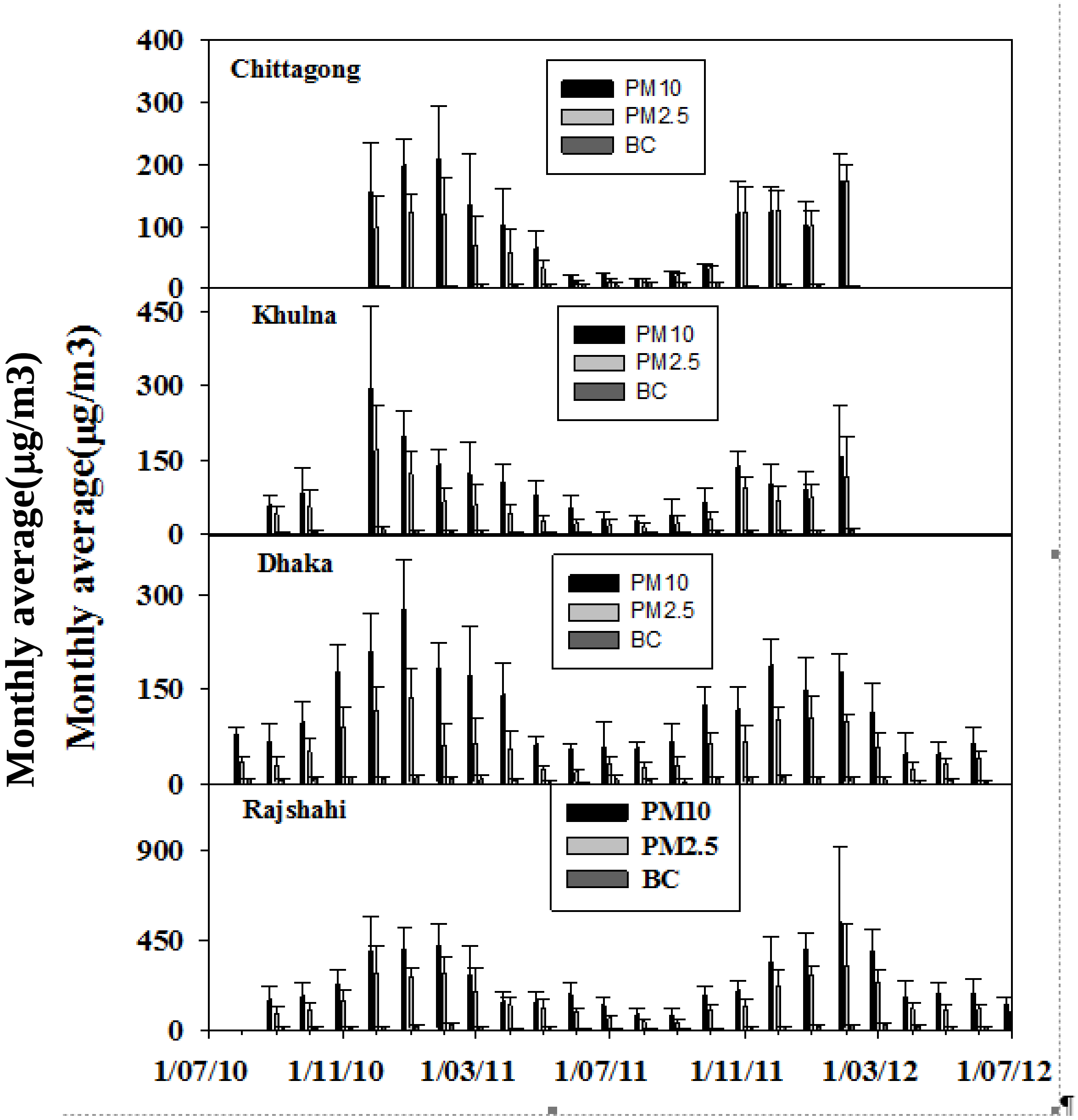

Figure 6: Variation of monthly average with time in different cities

Table 2 presents a summary of annual PM_{10}, $PM_{2.5}$, and BC concentrations at Rajshahi, Dhaka, Khulna, and Chittagong from September 2010 to July 2012. It can be seen from the Table 2 that the standard deviations of PM_{10}, $PM_{2.5}$ mass and BC concentrations are very large because of significant day-to-day variations. Variations in emissions as well as meteorological factors such as wind speed and wind direction drive this variability. The meteorology is responsible for dispersion and dilution of the pollutants in the atmosphere. Anthropogenic activities in Dhaka or Chittagong are much higher in general than Rajshahi. However, the PM and BC concentrations are much higher in Rajshahi. More importantly, it appears for Chittagong that a majority of the $PM_{2.5}$ in the summer monsoon season is BC (see also Table 6).

Table 2: The summary of PM and BC concentrations (µg/m³) during the sampling periods.

Parameter	Rajshahi			Dhaka			Khulna			Chittagong		
	PM10	PM2.5	BC	PM10	PM2.5	BC	PM10	PM2.5	BC	PM10	PM2.5	BC
Min	24.3	14.9	3.07	21.1	14.3	1.05	10.3	6.20	1.44	13.2	9.34	0.84
Max	1526	842	46.1	419	212	17.2	579	371	23.0	345	211	11.4
Mean	244	155	13.1	130	65.1	7.20	112	64.7	5.84	117	73.3	4.32
STD	172	112	7.05	74.2	41.2	3.31	88.4	56.8	3.58	78.5	50.7	2.67
Median	204	121	10.8	119	56.0	7.40	95.6	52.0	5.2	111	74.2	3.32
Sample size	211			185			145			114		
Sampling period	01/09/2010 to 31/07/2012			23/08/2010 to 01/07/2012			16/09/2010 to 23/02/2012			03/12/2010 to 29/02/2012		

Tables 3, 4, 5, and 6 show the seasonal variations of PM and BC in the four major cities. PM concentrations are seen to be higher in all 4 cities than the annual average NAAQS for $PM_{2.5}$ and PM_{10}; in winter these values are higher than other seasons. It has found that in winter, the $PM_{2.5}/PM_{10}$ ratio is high due to high $PM_{2.5}$. Alternatively, for Chittagong the ratio of $BC/PM_{2.5}$ becomes high in the monsoon season due to that a majority of the $PM_{2.5}$ is being analyzed as BC. Except for Rajshahi, the PM concentrations are almost same in all cities within standard deviation. Although anthropogenic activities and related emissions in Dhaka are much higher in general than the other cities, it was found that the average fine PM concentration of Rajshahi city was twice that of Dhaka and the other cities. However, placement of the site locations (in relation to local influencing sources) vary for each city, and play a part in this.

Table 3: Seasonal variation at Rajshahi of daily mean values

Year	Season	PM10		PM2.5		PM2.5/PM10		BC		BC/PM2.5	
		Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD
2010-2011	Post-monsoon	208	95.4	127	66.4	0.60	0.08	9.86	2.24	0.09	0.04
	Winter	408	131	277	94.0	0.69	0.09	18.45	5.68	0.07	0.02
2011-2012	Pre-monsoon	188	112	143	79.6	0.80	0.17	9.56	2.42	0.08	0.03
	Monsoon	114	58.0	55.4	26.5	0.50	0.09	7.27	2.18	0.15	0.05
	Post-monsoon	184	46.0	109	31.84	0.59	0.04	9.45	1.78	0.09	0.03
	Winter	431	245	271	140	0.63	0.08	17.63	6.66	0.07	0.05
2012	Pre-monsoon	253	132	151	77.5	0.61	0.12	19.73	9.49	0.14	0.04
	Monsoon	150	56.7	100	28.2	0.70	0.14	14.96	3.42	0.16	0.05

Table 4: Seasonal variation at Dhaka

Year	Season	PM10		PM2.5		PM2.5/PM10		BC		BC/PM2.5	
		Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD
2010-2011	Monsoon	69.0	25.5	30.3	11.6	0.44	0.08	5.10	1.44	0.18	0.04
	Post-monsoon	133	55.3	68.6	32.7	0.51	0.08	7.98	2.29	0.13	0.05
	Winter	221	71.2	104	49.8	0.45	0.13	8.89	2.38	0.12	0.14
2011-2012	Pre-monsoon	133	74.3	50.0	35.5	0.36	0.08	5.90	3.80	0.12	0.02
	Monsoon	60.0	21.6	26.8	10.5	0.46	0.13	4.40	2.89	0.17	0.08
	Post-monsoon	122	32.0	65.8	21.4	0.54	0.07	8.92	2.65	0.14	0.05
	Winter	172	44.9	101	23.6	0.61	0.11	9.85	1.72	0.10	0.02
2012	Pre-monsoon	73.6	47.8	39.1	23.1	0.56	0.09	5.45	3.20	0.15	0.05
	Monsoon	67.7	26.6	41.3	11.1	0.63	0.11	2.77	1.15	0.08	0.06

Table 5: Seasonal variation at Khulna

Year	Season	PM10		PM2.5		PM2.5/PM10		BC		BC/PM2.5	
		Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD
2010-2011	Post-monsoon	76.5	44.2	51.3	29.3	0.67	0.06	5.81	2.53	0.13	0.04
	Winter	211	118	120	72.9	0.56	0.12	8.76	4.30	0.08	0.02
2011-2012	Pre-monsoon	102	46.1	42.5	28.9	0.40	0.11	4.05	1.94	0.11	0.05
	Monsoon	40.6	24.6	19.6	11.8	0.53	0.18	2.69	0.99	0.16	0.07
	Post-monsoon	101	47.0	63.1	37.8	0.59	0.15	5.97	1.65	0.15	0.12
	Winter	115	67.0	84.6	52.6	0.74	0.14	7.97	3.34	0.10	0.03

Table 6: Seasonal variation at Chittagong

Year	Season	PM10		PM2.5		PM2.5/PM10		BC		BC/PM2.5	
		Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD
2010-2011	Winter	187	72.2	113	47.4	0.60	0.06	2.44	0.98	0.04	0.05
2011-2012	Pre-monsoon	107	67.6	56.6	39.4	0.51	0.08	4.81	2.14	0.17	0.19
	Monsoon	20.0	4.73	11.7	2.32	0.60	0.10	7.43	2.32	0.66	0.24
	Post-monsoon	85.1	59.9	60.5	45.9	0.72	0.17	5.43	3.21	0.20	0.20
	Winter	130	48.4	91.7	33.7	0.71	0.11	3.36	2.19	0.06	0.11

Examining the meteorological conditions (2010 to 2012) (See Appendix A), it is seen that during winter, the wind comes mainly from the north and northwest [24]. It can be observed that with the change of the season, the $PM_{2.5}$ mass also changes. Low humidity also plays an important role in this respect. The reasons for the high peaks during the winter are not only caused by seasonal fluctuations of the emissions, but also by meteorological effects. The Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT 4) model [23] was used to calculated the air mass backward trajectories for days with high impacts of fine particles at Rajshahi, Figure 10. Backward trajectories starting at height of 500 m above ground level were computed using the vertical mixing model. Figure 7 shows the contributions on 22 December 2010 and 12 February 2012 were likely due to transport from the north and north-westerly directions. These results indicate that PM concentrations in winter can at times be highly influenced by trans-boundary air pollution.

3.3 Long range transport of Fine $PM_{2.5}$ and BC

In order to identify trans-boundary influences, the effect of local contributions was minimized using a threshold value to define high values set as $2 * std\ dev + mean$ in case of measured fine PM[25]. Table 7 shows the mean, standard deviation, and the threshold values for $PM_{2.5}$ and black carbon concentrations. There is then the possibility of trans-boundary events [26] affecting local air quality. The maximum $PM_{2.5}$ concentrations in Dhaka, Khulna and Chittagong are 147, 178, and 175 $\mu g/m^3$, (Mean+2STD) respectively considering all local impacts. Bangladesh has a very flat landscape, and the concentrations should be similar in all areas with variation due to local sources. Hence the expected maximum concentration can be estimated as 184 $\mu g/m^3$ (Mean+2STD) (Here mean is the average of threshold value of Dhaka, Khulna and Chittagong). However, the threshold value of fine PM concentrations in Rajshahi is 379 $\mu g/m^3$. Thus, it can be concluded that the $PM_{2.5}$ concentrations above than 184 $\mu g/m^3$ may come from the trans-boundary transport, in which the value is 195 μ/m^3 (Subtracting 184 μ/m^3 from 379 μ/m^3).

Table 7: The daily mean, standard deviation and peak value of Fine PM2.5 and Black Carbon (BC) concentrations (μg/m^3) during the studying period.

Parameter	Statistics	Rajshahi	Dhaka	Khulna	Chittagong
Fine PM2.5	Mean	155	**65.1**	64.7	73.3
	Median	121	**56.0**	52.0	74.2
	STD	112	**41.2**	56.8	50.7
	Threshold Value	379	**147**	178	175
BC	Mean	**13.1**	**7.20**	5.84	4.32
	Median	**10.8**	**7.40**	5.20	3.32
	STD	**7.05**	**3.31**	3.58	2.67
	Threshold Value	**27.2**	**13.8**	13	9.66

On the other hand, the threshold value of BC concentrations in Dhaka, Khulna and Chittagong are 13.8, 13, and 9.66 ug/m^3 (Mean+2STD), respectively considering all local black carbon sources. Therefore the expected maximum concentration can be estimated as 14.4 ug/m3 (Mean+STD) (here mean is the average of threshold value of Dhaka, Khulna and Chittagong). However, the threshold value of BC concentration in Rajshahi is 27.2μg/m^3. Thus, it can be concluded that the BC concentrations above than 14.4 μg/m3 may come from the trans-boundary transport and the value is 12.8 μg/m^3 (subtracting 14.4 μg/m^3 from 27.2 μg/m^3)

It was found from the previous source apportionment study [12-27-28] that about 50.4% of total fine PM came from biomass burning/brick kilns [11]. It has also found that concentrations of O_3, CO, SO_2 and NO_X are lower than the corresponding NAAQS [1]. Figure 3 shows the time series plot for the fine PM concentrations in all 4 cities during the study period. It was found that there were two large peaks on 22 December 2010 and 12 February 2012 in case of Rajshahi with values of 635 μg/m^3 and 841 μg/m^3, respectively.

To explore the possibility of long-range transport of $PM_{2.5}$ to Rajshahi back trajectories were calculated starting at 500 m for 22 December 2010 and 12 February 2012 (5 days). Figure 7 shows representative trajectories.

From the NASA web site (http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=47742) (Supplemental Figure S1), it was found that haze hugged the southern face of the Himalaya in early December 2010. The haze resulted from a combination of agricultural fires combined with urban and industrial pollution, and a regional temperature inversion. In the wintertime, temperature inversions are common in Bangladesh trapping pollutants along with cold air at the surface, contributing to the build-up of haze.

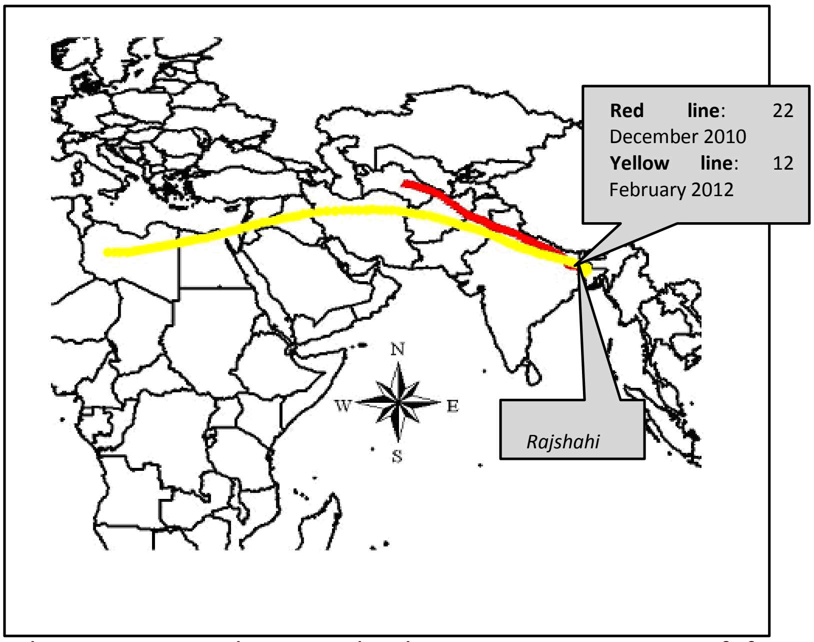

Figure 7: Air parcel back trajectories showing the long range transport of fine PM on December 22, 2010 and February 12, 2012.

Figure S1. Pollution and fog mixed at the base of the Himalayas in India in early December 2010 http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=47742

4 Discussion

Measurements of PM have shown that the highest concentrations occurred during the winter dry season. This also applied to Chittagong, except for BC which shows a maximum (and high BC/PM2.5 ratio) in the summer monsoon season possibly due to higher rainfall (Figure 5). Average concentrations measured in Rajshahi have generally been higher than in the other cities which can be contributed to regional and long-range transport of pollutants. In addition, this could also be due to intermittent local sources in the vicinity to the sampling station in Rajshahi. Specifically, the high PM concentrations seen in February 2012 might be due in part to a regional dust storm. The satellite image for this date (Supplemental Figure S2) shows a dust storm stretching across the Arabian Peninsula in early February 2012. This dust storm follows a familiar pattern for this region (http://thewatchers.adorraeli.com/2012/02/06/dust-storm-in-saudi-arabia/), with especially thick dust occurring in Saudi Arabia's southwest.

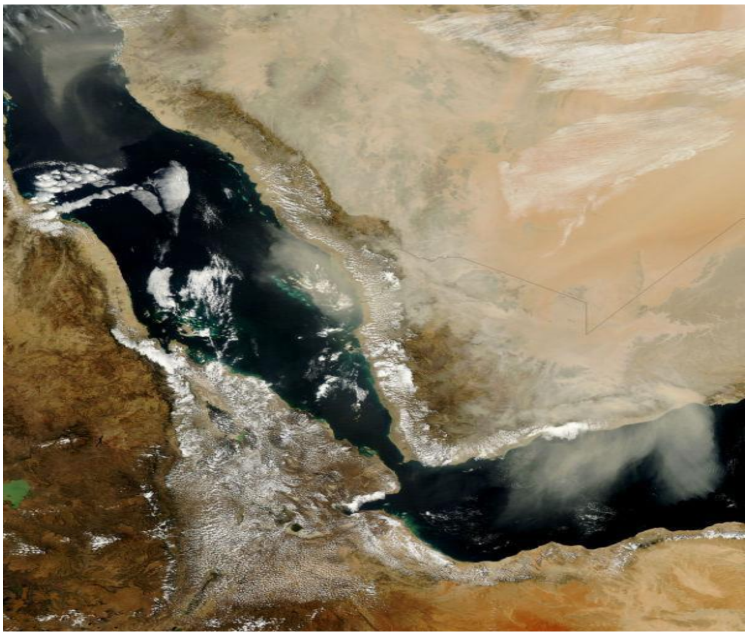

Figure S2: Dust storm over the Arabian Peninsula
http://thewatchers.adorraeli.com/2012/02/06/dust-storm-in-saudi-arabia/

5 Aknowledgements

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6 References

[1] Hak, C., Sivertsen, B., Randall, S. (2012) Bangladesh Air Pollution Studies (BAPS): Task 3 (Source apportionment) Inception report. June, 2012. Kjeller, NILU.

[2] Suthawaree, J., Jones, H.A.S.E., Kato, S., Kunimi, H., Kabir, A.N.M.H., Kajii, Y. (2012) Influence of extensive compressed natural gas (CNG) usage on air quality. *Atmos. Environ., 54,* 296-307.

[3] Francisco, A.d., Morris, J., Hall, A.J., Schellenberg, J.R.M.A., Greenwood, B.M. (1993) Risk factors for mortality from acute lower respiratory tract infections in young Garbian childen. *Int. J. Epidemiol., 22,* 1174-1182.

[4] Dockery, D.W., Speizer, F.E., Stram, D.O., Ware, J.H., Spengler, J.D., Ferris, B.G. (1989) Effects of inhalable particles on respiratory health of children. *Am. Rev. Diseases, 139,* 134-139.

[5] Dockery, D.J., Pope, C.A. (1994) Acute respiratory effects of particulate air pollution. *Ann. Rev. Public. Health, 15,* 107-132.

[6-7] Begum, B.A., Hossain, A., Saroar, G., Biswas, S.K., Nasiruddin, M., Nahar, N., Chowdury, Z., Hopke, P.K. (2011) Sources of carbonaceous materials in the airborne particulate matter of Dhaka. *Asian J. Atmos. Environ., 5,* 237-246.

[8] Begum, B.A., Biswas, S.K., Markwics, A., Hopke, P.K. (2010) Identification of sources of fine and coarse particulate matter in Dhaka, Bangladesh. *Aerosol Air Qual. Res., 10,* 345-353.

[9] Begum, B.A., Biswas, S.K., Nasiruddin, M., Hossain, A.M.S., Hopke, P.K. (2009) Source identification of Chittagong aerosol by receptor modeling. *Environ. Eng. Sci., 26,* 679-689.

[10] Begum, B.A., Biswas, S.K., Pandit, G.G., Saradhib, I.V., Waheed, S., Siddique, N., Seneviratne, M.C. S. Cohen, D.D., Markwitz, A., Hopke, P.K. (2011) Long range transport of soil dust and smoke pollution in the South Asian Region. *Atmos. Pollut. Res., 2,* 151-157.

[11] Begum, B.A., Biswas, S.K., Kim, E., Hopke, P.K., Khaliquzzaman, M. (2005) Investigation of sources of atmospheric aerosol at a hot spot area in Dhaka, Bangladesh. *J. Air Waste Manag. Assoc., 55,* 227-240.

[12] Begum, B.A., Hopke, P.K. (2013) Identification of haze creating sources from fine particulate matter in Dhaka aerosol using carbon fractions. *J. Air Waste Manag. Assoc., 63,* 1046-1057.

[13] Begum, B.A., Biswas, S.K., Nasiruddin, M., Hossain, A.M.S., Hopke, P.K. (2009) Source identification of Chittagong aerosol by receptor modeling. *Environ. Eng. Sci., 26,* 679-689

[14] Begum, B.A., Kim, E., Biswas, S.K., Hopke, P.K., (2004) Investigation of sources of atmospheric aerosol at urban and semi-urban areas in Bangladesh. *Atmos. Environ.,38,* 3025-3038.

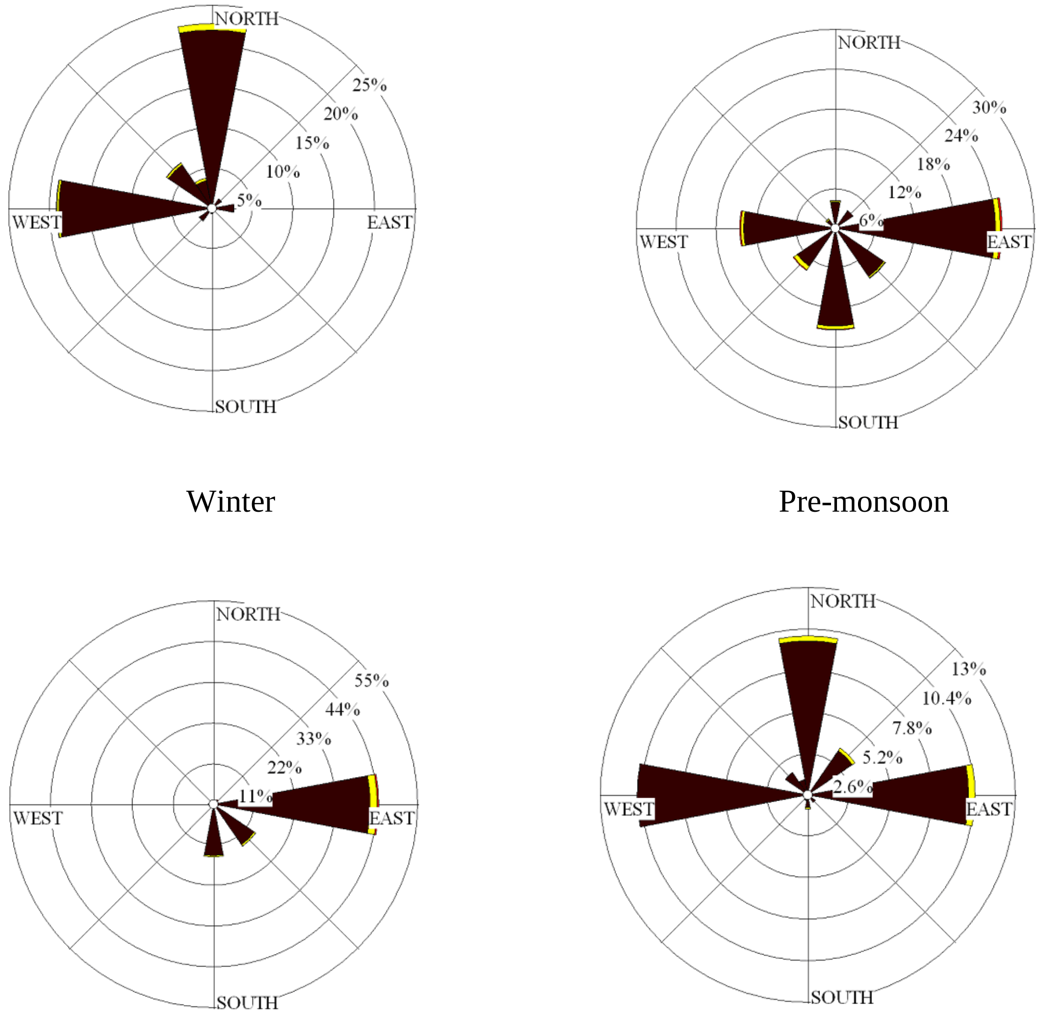
[15] Begum, B.A., Biswas, S.K. (2005) Comparison of PM collection efficiency of Gent and Airmatrics minivol portable air sampler. *Nucl. Sci. Appl., 14,* 79-83.

[16] Begum, B.A., Akhter, S., Sarker, L., Biswas, S.K. (2006) Gravimetric analysis of air filters and quality assurance in weighing. *Nucl. Sci. Appl., 15,* 36-41.

[17] Hansen, A.D., Rosen, H., Novakov, T. (1984) The aethalometer - an instrument for the real time measurements of optical absorption by aerosol particles. *Sci. Tot. Environ., 36,* 191-196.
[18] Wang, Y., Huang, J., Zananski, T.J., Hopke, P.K., Holsen, T.M. (2010) Impacts of the Canadian forest fires on atmospheric mercury and carbonaceous particles in Northern New York. *Environ. Sci. Technol., 44,* 8435-8440.
[19] Wang, Y., Hopke, P.K., Rattigan, O.V., Zhu Y. (2011) Characterization of ambient black carbon and wood burning particles in two urban areas. *J. Environ. Monit., 13,* 1919-1926.
[20] Salam, A., Bauer, H., Kassin, K., Ullah, S.M., Puxbaum, H. (2003) Aerosol chemical characteristics of a mega-city in Southeast Asia (Dhaka, Bangladesh). *Atmos. Environ., 37,* 2517-2528.
[21] Begum, B.A., Hopke, P.K., Markwitz, A. (2011) Status of air quality: Experience in Bangladesh. Submitted.
[22] Begum, B.A., Biswas, S.K., Hopke, P.K. (2008) Assessment of trends and present ambient concentrations of $PM_{2.2}$ and PM_{10} in Dhaka, Banglaesh. *Air Qual. Atmos. Health, 1,* 125-133.
[23] Draxler, R.R., Rolph, G.D. (2003) HYSPLIT 4(Hybrid Single-Particle Lagrangian Integrated Trajectory). Silver Spring, MD, NOAA Air Resources Laboratory.
[24] Begum, B.A., Biswas, S.K., Hopke, P.K. (2006) Temporal variations and spatial distribution of ambient PM2.2 and PM10 concentrations in Dhaka, Bangladesh. *Sci. Tot. Environ., 358,* 36-45.
[25] Begum, B.A., Biswas, S.K., Pandit, G.G., Saradhi, I.V., Waheed, S., Siddique, N., Seneviratne, M.C.S., Cohen, D.D., Markwitz, A., Hopke, P.K. (2011) Long range transport of soil dust and smoke pollution in the south Asian region. *Atmos. Pollut. Res., 2,* 151-157.
[26] Adhikary, B., Carmichael, G.R., Tang, Y., Leung, L.R., Qian, Y., Schauer, J.J., Stone, E.A., Ramanathan, V., Ramana, M.V. (2007) Characterization of the seasonal cycle of south Asian aerosols: A regional-scale modeling analysis. *J. Geophys. Res., 112,* D22S22, doi:10.1029/2006JD008143.
[27] Begum, B.A., Biswas, S.K., Markwitz, A., Hopke, P.K. (2010) Identification of sources of fine and coarse particulate matter in Dhaka, Bangladesh. *Aerosol Air Qual. Res., 10,* 345-353.
[28] Begum, B.A., Biswas, S.K., Hopke, P.K. (2011) Key issues in controlling air pollutants in Dhaka, Bangladesh. *Atmos. Environ., 45,* 7705-7713.

Appendix A

Wind roses by season for each sample city



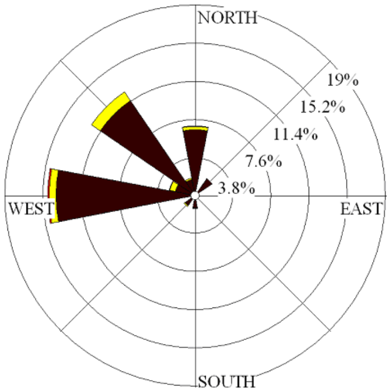
Winter

Pre-monsoon

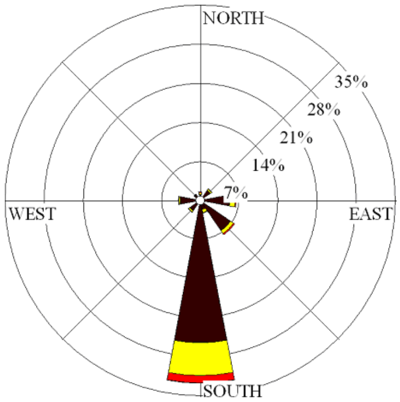
Monsoon

Post-monsoon

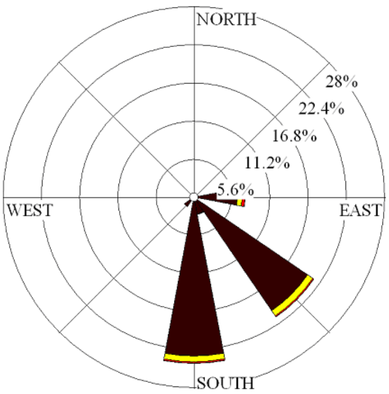
Figure A-1: Winter, Pre-monsoon, Monsoon, Post-monsoon seasons respectively for Rajshahi City



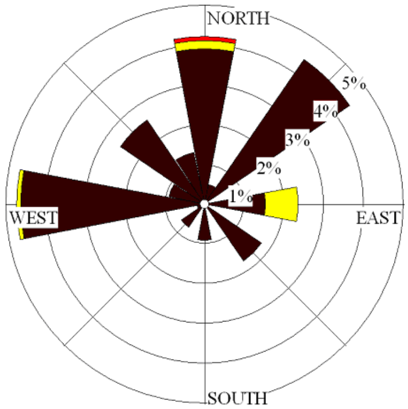
Winter



Pre-monsoon

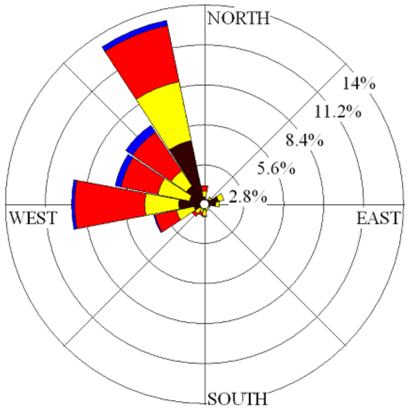


Monsoon

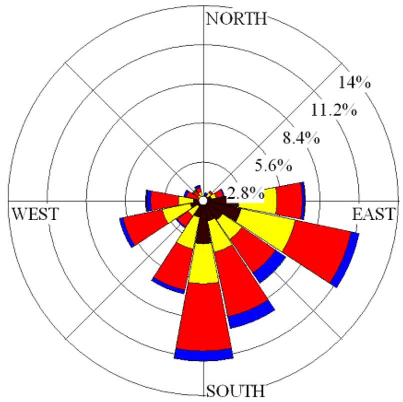


Post-monsoon

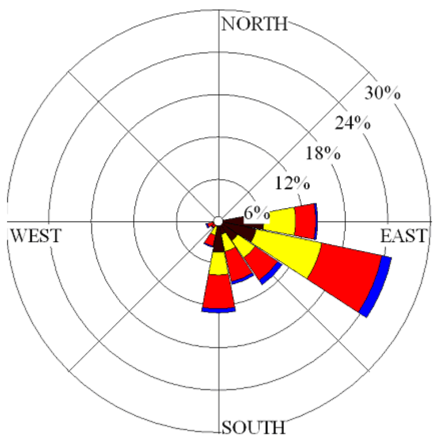
Figure A-2: Winter, Pre-monsoon, Monsoon, Post-monsoon seasons respectively for Dhaka City



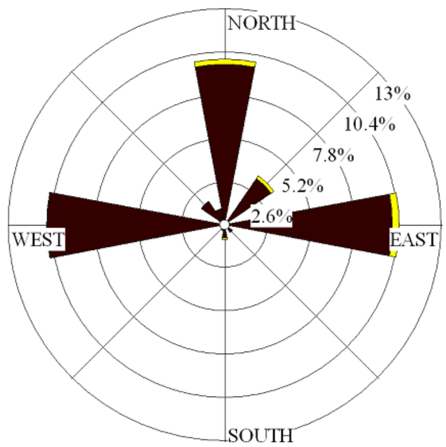
Winter



Pre-monsoon



Monsoon



Post-monsoon

Figure A-3: Winter, Pre-monsoon, Monsoon, Post-monsoon seasons respectively for Chittagong City

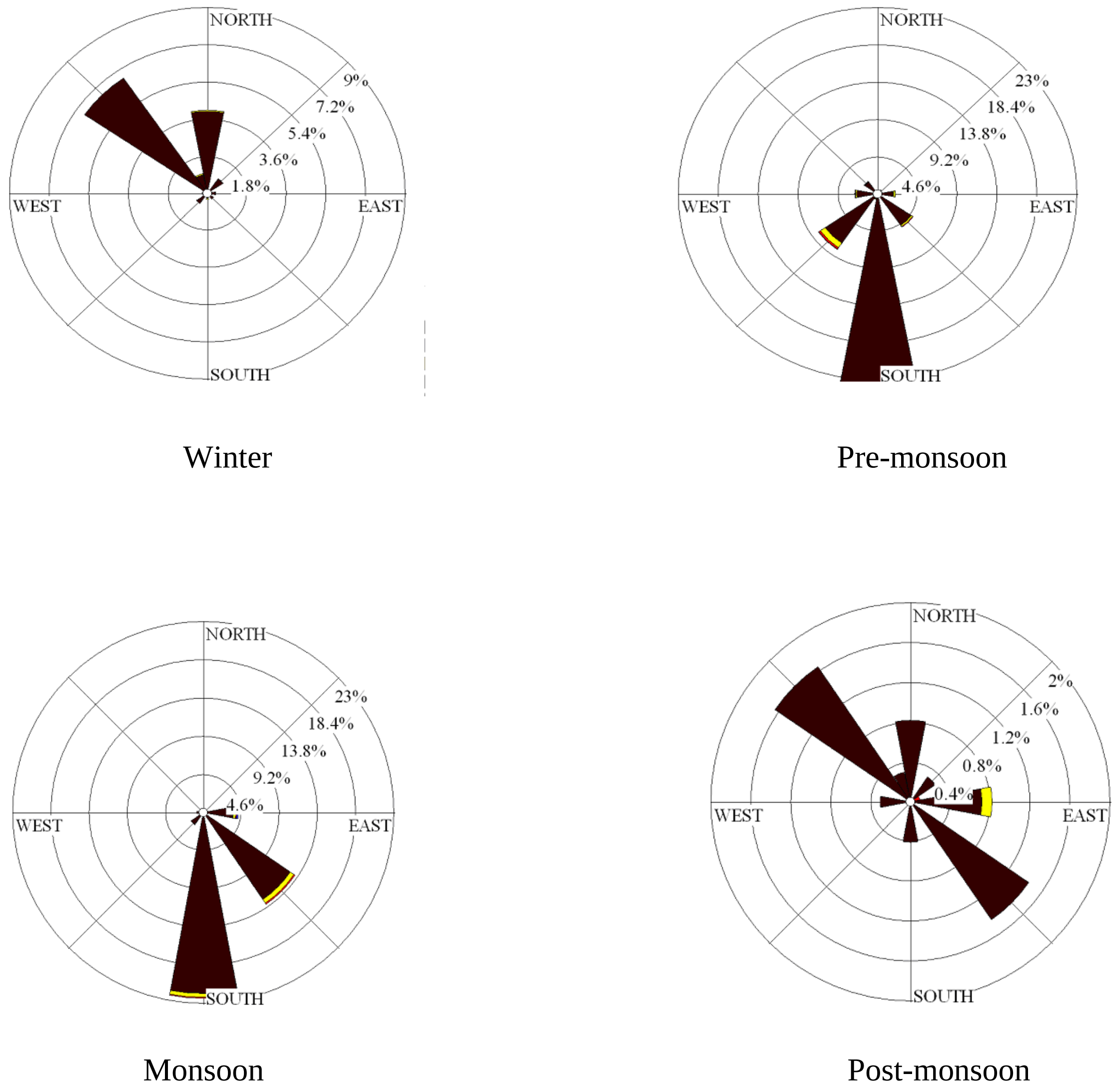


Figure A-4: Winter, Pre-monsoon, Monsoon, Post-monsoon seasons respectively for Khulna City

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PROJECT LEADER
Scott Randall

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O-111091

AUTHOR(S)
Bilks A. Begum, Scott Randall, Bjarne Sivertsen

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ABSTRACT
As a part of the Bangladesh Air Pollution Studies (BAPS) project, an analysis of PM and BC samples was performed for four cities in Bangladesh.
Four major cities, Rajshahi, Dhaka, Khulna and Chittagong have been suffering for many years with severe air pollution particularly by particulate matter (PM). PM samples were collected between September 2010 to July 2012 at four Continuous Air Monitoring Stations (CAMS) located at Farm Gate in Dhaka, Sapura in Rajshahi, Baira in Khulna and a TV station, Khulshi in Chittagong. PM sampling was performed using dichotomous samplers, which collect samples in two sizes: $PM_{2.5}$ and $PM_{2.5-10}$.
Data reveal that the pollution from particulate matter varies greatly with climatic conditions. It was found that the PM and BC concentrations in Rajshahi were higher than the other three cities.

NORWEGIAN TITLE

KEYWORDS		
PM, Particles	Urban environment	Bangladesh

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