Organic and Black Carbon in PM$_{2.5}$ at an Urban Site at Dhaka, Bangladesh

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ABSTRACT

The results from 1-year of measurements of PM$_{2.5}$, organic carbon (OC) and black carbon (BC) concentrations are presented for an urban traffic-influenced site, the Farm Gate in Dhaka, Bangladesh. The measurements were based on sampling using two Air Metrics simultaneously operating samplers. The concentrations of OC and BC concentrations in PM$_{2.5}$ varied from 5–96 µg/m^3 and 4–48 µg/m^3, respectively. The concentrations of PM$_{2.5}$ varied from 11–328 µg/m^3. The annual particulate organic matter (POM) accounted for 46 ± 11% in PM$_{2.5}$ whereas BC stayed at 33 ± 12%. The effects of meteorological conditions on the variability of OC and BC concentration were examined and the contribution of secondary organic aerosol to the total OC was calculated. The concentrations of OC and BC relative to the total PM$_{2.5}$ are high and have good correlation with wind speed and temperature. The OC/BC ratio correlated with wind speed, temperature and sulfur concentration. Based on these relationships, it can be concluded that both local and regional sources of OC and BC are important. The local sources are traffic, coal and biomass burning. Distant sources include areas where there is extensive agricultural burning.

Keywords: PM$_{2.5}$; Organic carbon (OC); Black carbon (BC); Particulate organic matter (POM).

INTRODUCTION

Carbonaceous species, organic carbon (OC) and black carbon (BC), constitute a major, sometimes dominant fraction of atmospheric fine particulate matter. Black carbon, a short-lived climate forcer, or SLCF, has a short lifetime in the atmosphere, as in days to weeks and accounts for 30 to 40% of global warming. Black carbon is the principal light-absorbing species in the atmosphere, playing an important role in the aerosol climatic forcing (Jacobson, 2001). Because of its surface properties, BC provides good adsorption sites for many semi-volatile compounds such as the PAHs (Dachs *et al.*, 2000). Black carbon is an incredibly important global warming agent because it warms the earth in two ways. First, it absorbs light because of its dark color and radiates heat into the atmosphere, raising air temperature. Secondly, it also deposits on snow and ice, darkening the light surfaces, absorbing more heat and accelerating melting (Kerwald *et al.*, 2008). Reducing black carbon provides near-term benefits by slowing warming and ice melt. As a warming pollutant, black carbon is between 760 and 2600

times more potent than CO$_2$ on a 100 or 20 year basis, respectively (Bond *et al.*, 2011).

Alternatively, OC effectively scatters light and may contribute significantly to both visibility degradation and the direct aerosol climatic forcing (Malm *et al.* 2000; Tegen *et al.*, 1997). A significant fraction of the particulate OC is water soluble, making it important in particle–cloud interactions (Corrigan *et al.*, 1999; Decesari *et al.,* 2000). Finally, carbonaceous species have the potential to influence many heterogeneous reactions involving atmospheric particles and trace gases (Grgic *et al.*, 1998; Lary *et al.*, 1999). Although BC and OC are important in atmospheric chemistry and physics, information concerning their spatial and temporal variability is quite limited. Most of the available data include only one particle size fraction, and the overall measurement period rarely exceeds a few weeks (Castro *et al.*, 1999; Lin *et al.*, 2001). Various analysis methods to distinguish between OC and BC have been employed. It has found that organic matter containing hydrogen obtained from the IBA analysis had a good correlation with organic carbon which has obtained from carbon analysis method. On the other hand elemental carbon obtained from carbon analysis shows good correlation with the black carbon which has obtained from reflectance measurement (Salako *et al.*, 2012).

In this paper, a yearlong set of daily BC and OC

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concentrations in both $PM_{2.5}$ and size fraction (particulate matter below 2.5) will be presented. The measurements have been performed at a traffic-influenced site, Farm Gate in Dhaka, Bangladesh. Sampling of particulate matter has been done using AirMetric MiniVol samplers, and the subsequent determination of BC and OC concentrations are based on reflectometer and thermal–optical carbon analyses, respectively. The main aim is to provide a comprehensive data set on the concentration and variability of atmospheric OC and BC in this specific measurement site. The contributions of OC and BC to the total fine particulate mass will be determined, and the role of different meteorological variables will be investigated. The relative importance of primary versus secondary OC sources will be estimated.

METHODS

Site Description and Measurement Period

The measurements were carried out at an urban site at Dhaka. PM samplings were performed using Air Metrics

MiniVol sampler for collecting $PM_{2.5}$ samples from the Farm Gate, continuous air monitoring station (CAMS) site (Fig. 1) in Dhaka city. Farm Gate is a hot spot site (Latitude: 23.76°N; Longitude: 90.39°E) due to the proximity of several major roadways intersection and large numbers of vehicles plying through the area (Begum *et al.*, 2005). The site is in the mixed area (i.e., commercial and semi industrial area). The Tejgaon industrial area is very near to the site.

The Air Metrics MiniVol sampler developed jointly by the U.S. Environmental Protection Agency (EPA) and the Lane Regional Air Pollution Authority was used for and $PM_{2.5}$ sampling (Baldauf *et al.*, 2001). At the Farm Gate site, the samplers were placed on the flat roof of the guardhouse of Bangladesh Agricultural Research Council (BARC). This location is known as CAMS site started from 2009 handled by Department of Environment (DoE) in Dhaka. The MiniVols were programmed to sample at 5 L/min through $PM_{2.5}$ particle size separator (impactor) and then through 2 μm pore Teflon and quartz filters in the two samplers. The actual flow rate should be 5 L/min at ambient
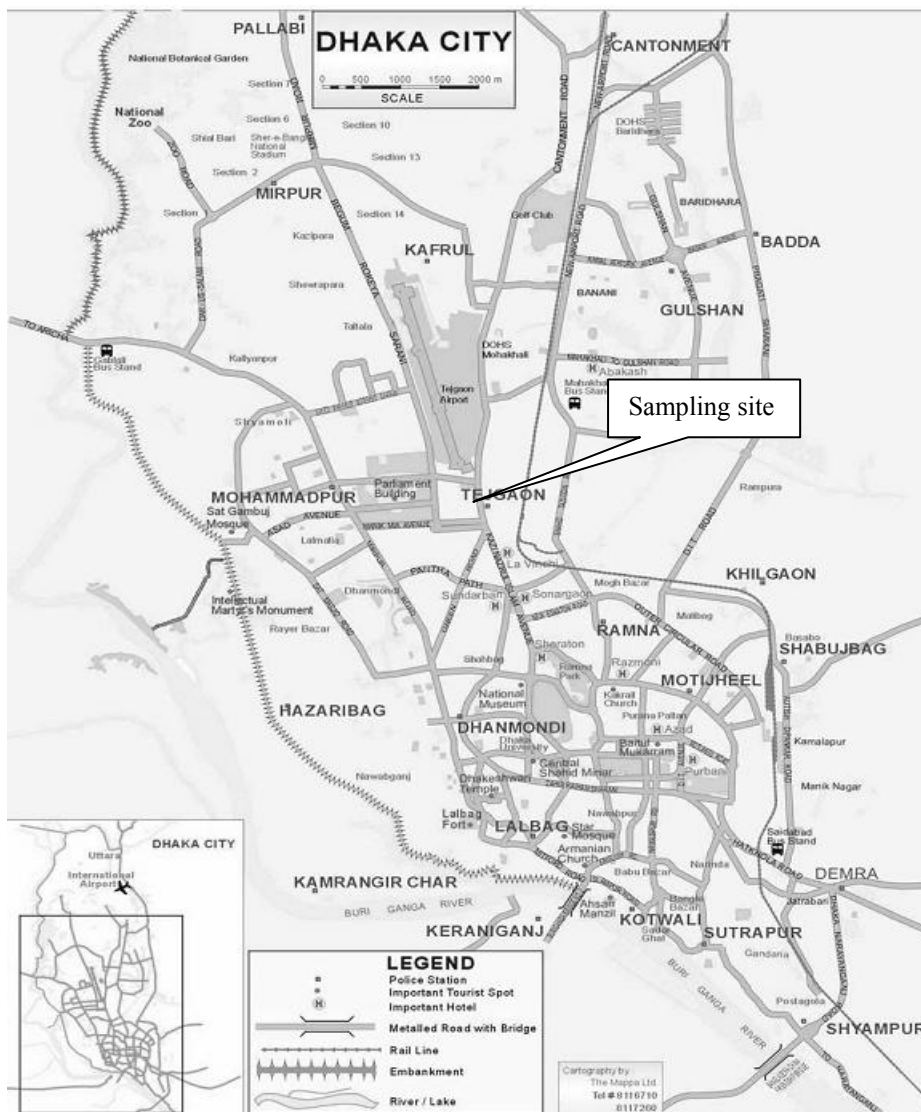

Fig. 1. Map of Dhaka, Bangladesh showing the location of the Farm Gate CAMS sampling site.

conditions for proper size fractionation. To ensure a constant flow of 5 L/min through the size separator at different air temperatures and ambient pressures, the sampler flow rates were adjusted for the ambient conditions at the sampling site. The MiniVol sampler was 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 for the Farm Gate area. The intake manifold at the Farm Gate location was located about 5 m away from the main road. Two samples of $PM_{2.5}$ were simultaneously collected on Teflon and quartz filters for 24 h with two MiniVol samplers. The inlets of the samplers were kept 45 cm apart from each other.

The sampling protocol was every third day starting from February 8, 2010 and continuing to February 28, 2011. The conditioned clean filters were loaded in their respective filter holder assembly at the CAMS conditioning room and were brought to sampling site in separate, clean polyethylene bag on each sampling day. After sampling, the filter holder assemblies (keeping the exposed filters inside) were brought to the conditioning room of Atomic Energy Centre Dhaka (AECD) directly from the sampling site for conditioning and PM mass measurement. Care was taken in transporting the exposed filter holder assemblies, so that there should be no PM loss. The loaded quartz filters were kept in a freezer at –20°C.

PM Mass, BC, and Carbon Fraction Analysis

PM mass was measured in the Chemistry Lab of the Atomic Energy Centre, Dhaka (AECD). The $PM_{2.5}$ samples were determined by weighing the filters before and after exposure using a microbalance (Begum *et al.*, 2006). The filters were equilibrated for 24h at constant humidity of 50% and 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 Teflon filters before each weighing. The difference in weights for each filter was calculated and the mass concentrations for each $PM_{2.5}$ samples were determined.

The $PM_{2.5}$ samples collected on Teflon filters were analyzed by an EEL-type Smoke Stain Reflectometer (Diffusion Systems, Ltd) to measure BC. Secondary standards of known black carbon concentrations were used to calibrate the reflectometer (Biswas *et al.*, 2003). The concentrations are defined based on the amount of reflected light that is absorbed by the filter sample and an assumed mass absorption coefficient. It is related to the concentration of light absorbing carbon through standards of carbon with known areal density. Iron (Fe) has a moderate light absorption coefficient and can have some limited influence on the BC value measured by reflectance. The uncertainty associated with the BC measurement is rather high (4–9%), and therefore, the influence of variation in Fe concentration on BC measurement has been neglected.

Carbonaceous materials collected on the $PM_{2.5}$ quartz filters were analyzed via IMPROVE/TOR protocol (Chow *et al.*, 1993; Chow *et al.*, 2008) for eight temperature resolved carbon fractions (Atmoslytic model DRI2100A). This protocol provides concentrations of carbon in four organic carbon fractions (OC1, OC2, OC3, OC4), three elemental carbon fractions (EC1, EC2, EC3) and pyrolyzed carbon (OP). The total OC is the sum of the fractions of OC1, OC2, OC3, OC4 and OP. The total EC is obtained as the sum of (EC1 – OP) + EC2 + EC3. The EC and BC values are well correlated for samples collected at this site (Salako *et al.*, 2012)

Multielemental Analysis

Multielemental analyses of the air particulate samples were made using Ion Beam Analysis (IBA) at the Institute of Geological and Nuclear Science (IGNS), New Zealand. The X-ray spectra obtained from IBA measurements were analyzed using the computer code GUPIX (Maxwell *et al.*, 1989, 1995). Elemental analyses from H to Pb were performed on the Teflon filters using IBA (Cohen *et al.*, 1996). The method is described in detail elsewhere (Landsberger and Creatchman, 1998).

Traffic Volume at the Sampling Site

A traffic survey was conducted by manual counting vehicles in the Farm Gate corridor in front of the sampling site during the study period to explore the relationship between PM concentrations and traffic volume. It was observed that the private cars were the primary motorized vehicles (80% of the total vehicles) plying this corridor. Some buses (large and medium) also ran on the roadways. It has observed that heavy-duty diesel trucks operate 17 times more frequently at night than during the day. Among the bus and minibuses, only a few buses run on CNG and most of the buses and minibuses have diesel engines.

Meteorological Conditions

In Bangladesh, the climate is characterized by high temperatures and high humidity most of the year and distinctly marked seasonal variations in precipitation. Based on the meteorological conditions (Salam *et al.*, 2003), the year can be divided into four seasons, pre-monsoon (March–May), monsoon (June-September), post-monsoon (October–November) and winter (December–February). The dispersion of PM strongly depends on the wind speed and direction (Begum *et al.*, 2008). Meteorological data for sampling dates was collected from the nearby meteorological station, which is located about 2 kilometers north of the sampling site.

RESULTS AND DISCUSSION

Dhaka, the eighth largest city in the world, has witnessed a rapid growth of urban population in recent times, which has contributed to rising demand for transport services, mainly road transport. As a result, the number of motor vehicles increased significantly in Dhaka. There has been a steep rise in a heterogeneous mixture of old technology vehicles despite that the road space narrowing and the traffic congestion reaching unmanageable proportions. As a result, major traffic intersections in the city have turned to hot spots for air pollution from vehicular emissions. The

government has adopted different policies especially for motor vehicles to reduce their emissions (Begum *et al.*, 2009). Hence, it has found that the current air quality in Dhaka is better although the numbers of vehicles has increased year by year (Begum *et al.*, 2011a). During recent years, most of the vehicles run by CNG fuels during the day. Therefore, PM emissions have been reduced. However, at night, heavy-duty diesel vehicles operate and emit large quantities of PM. Hence, at night the contribution of PM is higher than daytime.

Particulate Matter Mass, Organic Carbon and Black Carbon Concentrations

The 24-hour average BC, OC and PM$_{2.5}$ mass fraction results for the CAMS site are shown in Fig. 2 as monthly box and whisker plots. The box represents 25–75% of the distributions of the monthly BC, OC and PM$_{2.5}$ concentrations. The horizontal solid line in the box indicates the median and dotted line denotes the mean of the distribution for the month. The yearly average value (82.5 µg/m^3) for PM$_{2.5}$ mass during the study period is much higher than the yearly average Bangladesh National Ambient Air Quality Standard as well as 1997 USEPA standards, which is set at 15 µg/m^3. The points lying outside the range defined by the whiskers (extreme events) are plotted as outlier dots. The monthly average of OC, BC and PM$_{2.5}$ show low values during the rainy season and become higher during the rest of the year where the rainfall in minimum and temperature is low. Both OC and BC have seasonal variation (Fig. 2).

The concentration of OC also varies with temperature. This observation explains the complex and sensitive relationship between the different factors controlling the gas-particle partitioning. The observed variability in the OC concentrations could not be explained by simple photochemistry, but both OC and BC concentrations vary with temperature (Fig. 2) and wind speed (Fig. 3) and have seasonal variations. Thus, it may be concluded that this behavior is expected in case of transboundary events where local pollution is augmented. It is also found from the previous studies (Begum *et al.*, 2009; Begum *et al.*, 2011b) that the northwesterly wind in winter increased the concentrations of PM$_{2.5}$ and BC. BC is a tracer of primary anthropogenic emissions.
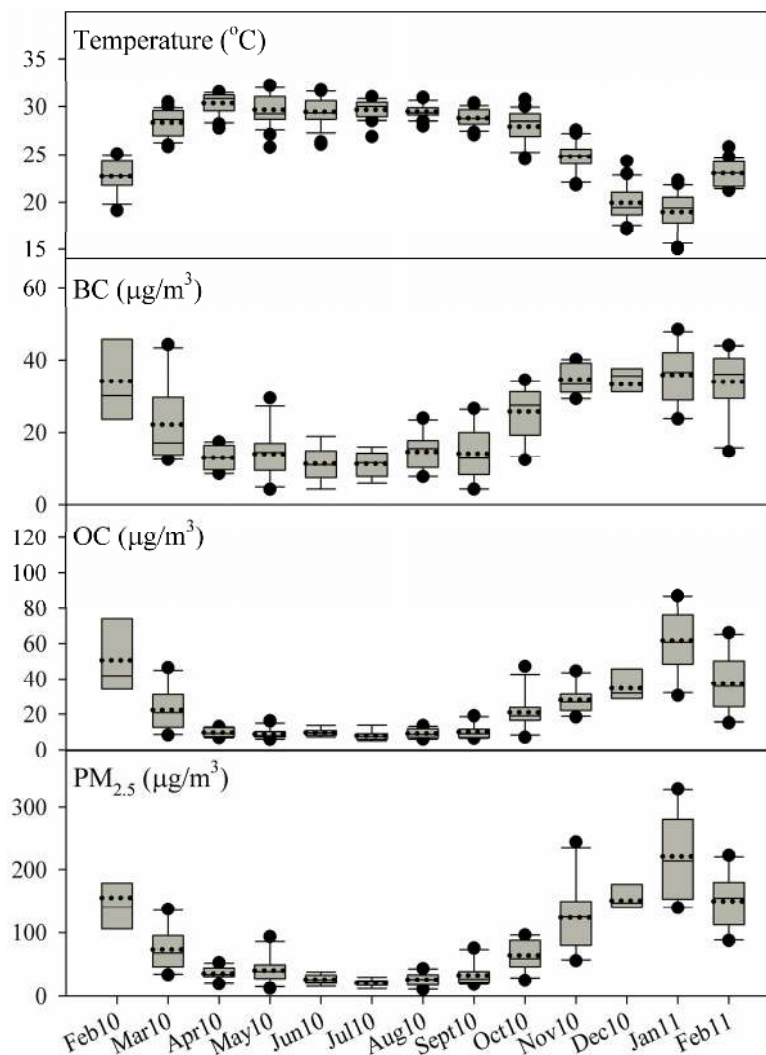

Fig. 2. Box and whisker plots describing the distributions of temperature, BC, OC, and PM$_{2.5}$.
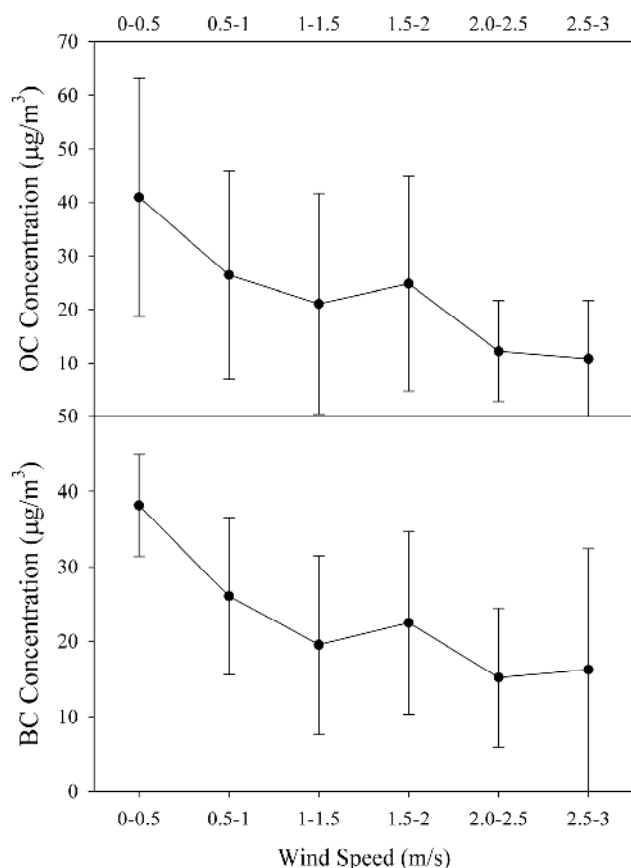
Fig. 3. Average concentrations of OC (top) and BC (bottom) for each wind speed interval.

When average BC concentrations were calculated for each wind speed class, a clear inverse correlation was observed between BC and wind speed (Fig. 3). Similar behavior was also observed for the OC fraction (Fig. 3). It has found that OC and BC comprised about 54% of the $PM_{2.5}$. The carbon content of organic compounds is determined by thermal methods and not the amount of other elements like H, O and N and also the present of these compounds. Hence in order to convert the measured amount of organic carbon to the total POM, the OC mass has to be multiplied with a factor that is an estimate of the average molecular weight per carbon weight for the organic aerosol. In order to convert the measured amount of carbon to the total particulate organic matter (POM), the OC mass was multiplied with 1.6 (Turpin and Lim, 2001). Primary OC emissions are typically thought to have a multiplier of 1.4 and for samples strongly influences by secondary organic aerosol, it could be as high as 2.1. The value of 1.6 was chosen as an intermediate value that provides values that achieve reasonable mass closure for these samples. Table 1 lists the monthly averaged contributions of POM and BC to the $PM_{2.5}$ mass concentration. The variability in these concentrations can be seen both by month as well as by season. POM and BC accounted for an annual average contribution to the total $PM_{2.5}$ of 46 ± 11% and 33 ± 12%, respectively.

OC concentrations was found to average POM contributions of 21–86% in $PM_{2.5}$. BC accounted for 4–59%

of the $PM_{2.5}$ mass concentrations. For comparison, the high average BC mass fractions (43 ± 20%) for $PM_{2.5}$ has reported in a traffic intersection in Paris (Ruellan *et al.*, 2001).

Contribution of Primary and Secondary OC

The concentration of primary and secondary sources for atmospheric OC can vary depending on the proximity and strength of these sources, photochemical activity, and the age of the aerosol. Under favorable conditions and close to a major primary source, OC can be mainly primary in origin. Primary OC that originates from combustion sources is principally in fine particles. Atmospheric BC is always primary in origin since it is not formed by atmospheric reactions. Most of the atmospheric BC resides in the fine particle size (Viidanoja *et al.*, 2002a). The mass size distribution of BC emitted from engines peaks at about 0.1 mm, but as a result of atmospheric processing, most of the BC is observed in the accumulation mode between 0.1 and 1 μm (Begum *et al.*, 2011a; Hitzenberger *et al.*, 2001).

Defining the Primary OC/BC Ratio

BC is used as a tracer of primary OC in $PM_{2.5}$ if the ratio of primary OC and BC for each source and the contribution of different sources at the measurement site are known. From this study, it has found that BC(EC)/TC ratio is 0.3 similar to other reports (Cachier *et al.*, 1991; Cachier *et al.*, 1995) (TC = OC + EC or BC). $PM_{2.5}$ in Dhaka also is enriched with emissions from biomass burning (local and regional). The concentration of secondary carbon OC_{sec} in $PM_{2.5}$ can be calculated from measured fine OC and BC using the following equation (Viidanoja *et al.*, 2002b);

$$OC_{sec} = OC_{PM2.5} - (OC/BC)_{prim} \times BC \qquad (1)$$

where $(OC/BC)_{prim}$ is the average primary OC/BC ratio.

To estimate the contribution of secondary carbon to the total particulate OC, some authors have used OC/BC ratio (Castro *et al.*, 1999; Lin and Tai, 2001). The primary OC/BC ratio has been estimate from atmospheric data assuming that the lowest observed OC/BC ratios represent the primary aerosol. The OC/BC ratios vary with temperature because of shifts in the gas/particle equilibrium of semi-volatile components (Fig. 4).

Ambient OC/BC Ratio

Fig. 5 presents the distributions of the monthly OC/BC ratios for the whole study period. This ratio varies between 0.25 to 2.34. OC to BC ratios depend on emission sources and secondary organic aerosol formation. It has found (Hildemann *et al.*, 1991) that OC/EC in fine particles of 2.2 for light-duty gasoline vehicles and 0.8 for heavy-duty gasoline vehicles. The OC/EC values in Kathmandu, Nepal were found to be greater than 3.01 but sampling was only performed in winter (Shakya *et al.*, 2010). It has also observed that the OC/BC ratio also varies with season. High OC/BC ratios in winter are the result of volatilization being increased at the lower temperatures. Higher ratios in June and September suggest that there was secondary organic aerosol (SOA) at the measurement site.

Table 1. Monthly means for POM and BC in PM2.5, OC/BC ratio, Secondary organic carbon (OCsec) and the contribution of OCsec to the total organic carbon in PM2.5 (OCsec/OCPM2.5)

| Month	POM/PM$_{2.5}$ (%)	BC/PM$_{2.5}$ (%)	OC/BC	OC$_{sec}$	OC$_{sec}$/OC$_{PM2.5}$ (%)
February 2010	51.3	22.5	1.44 ± 0.31	31.0 ± 15.9	61.2
March 2010	47.5	30.5	0.91 ± 0.35	9.9 ± 4.4	46.3
April 2010	45.3	37.9	0.77 ± 0.15	3.3 ± 1.5	32.3
May 2010	35.1	35.4	0.91 ± 1.03	3.1 ± 2.2	32.4
June 2010	57.0	40.9	1.00 ± 0.39	5.6 ± 1.8	55.8
July 2010	49.1	41.3	0.76 ± 0.24	3.8 ± 2.7	43.1
August 2010	44.5	43.2	0.67 ± 0.15	3.0 ± 1.6	32.7
September 2010	47.6	38.3	0.86 ± 0.39	3.2 ± 1.2	33.8
October 2010	53.0	41.5	0.82 ± 0.32	8.6 ± 6.7	39.6
November 2010	39.0	32.0	0.81 ± 0.16	6.5 ± 4.3	20.8
December 2010	37.0	24.5	1.02 ± 0.33	17.3 ± 11.6	44.7
January 2011	45.0	16.9	1.72 ± 0.38	35.5 ± 12.5	58.4
February 2011	42.0	25.2	1.08 ± 0.26	17.4 ± 10.3	44.5
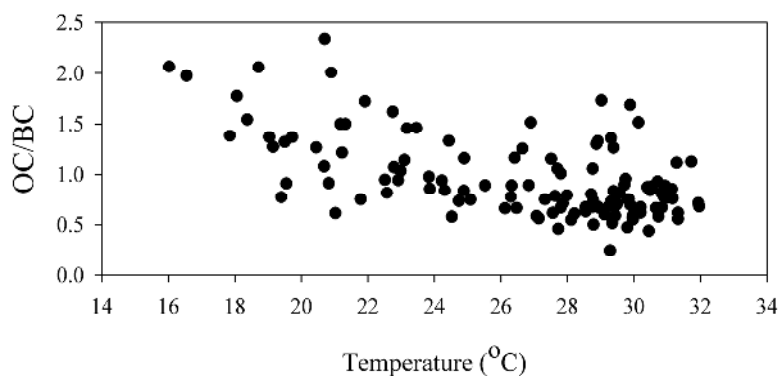
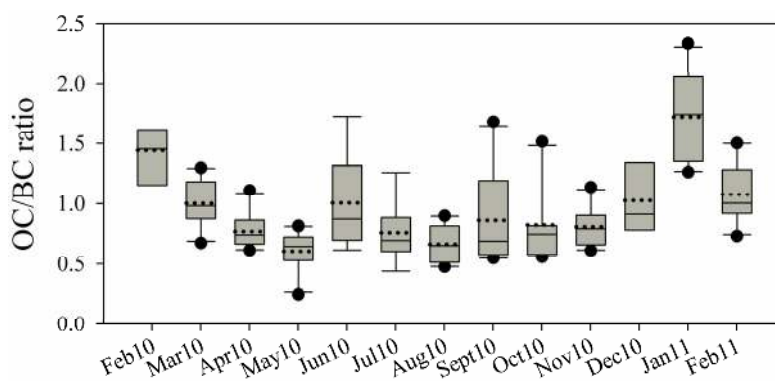**Fig. 4.** OC/BC ratio as a function of temperature.

Fig. 5. Box and whisker plots describing the monthly distributions of the OC/BC ratio.

The OC/BC ratio varies with temperature (Fig. 4) and wind speed (Fig. 6). At low wind speed and temperature, the OC/BC ratio is high and at high temperatures and wind speeds, the OC/BC ratio is low suggesting that higher ventilation, dilution and temperature may drive more of the OC to repartition into the gas phase.

Correlation of OC and BC Ratio with Sulfate Concentration

One major class of local SO$_2$ sources are brick kilns. The emitted SO$_2$ will have a limited impact on particulate sulfate in Dhaka because the atmospheric oxidation of SO$_2$ to sulfate is relatively slow. However, local gasoline and diesel fuels contain high sulfur concentrations (0.25%) resulting in significant emissions of SO$_3$ forming local primary sulfate. This local sulfate will interfere with the use of sulfate as a tracer for long-range transported secondary particles.

Fig. 7 shows the variation of OC with sulfur separated into the winter season (top) and the rest of the year (bottom). The analogous plot of BC against sulfur is provided in Fig. 8. There are significant differences between these plots. In
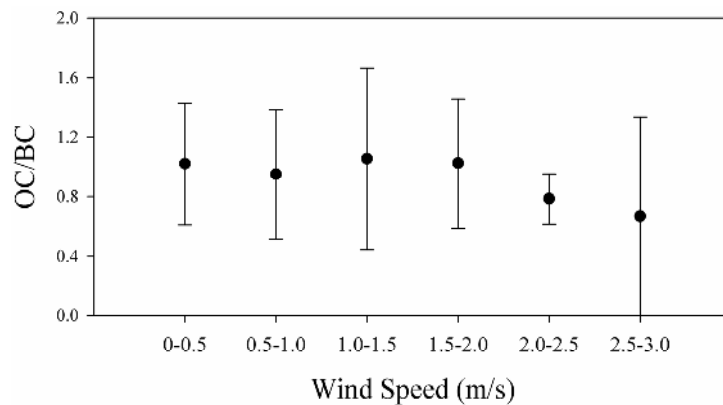
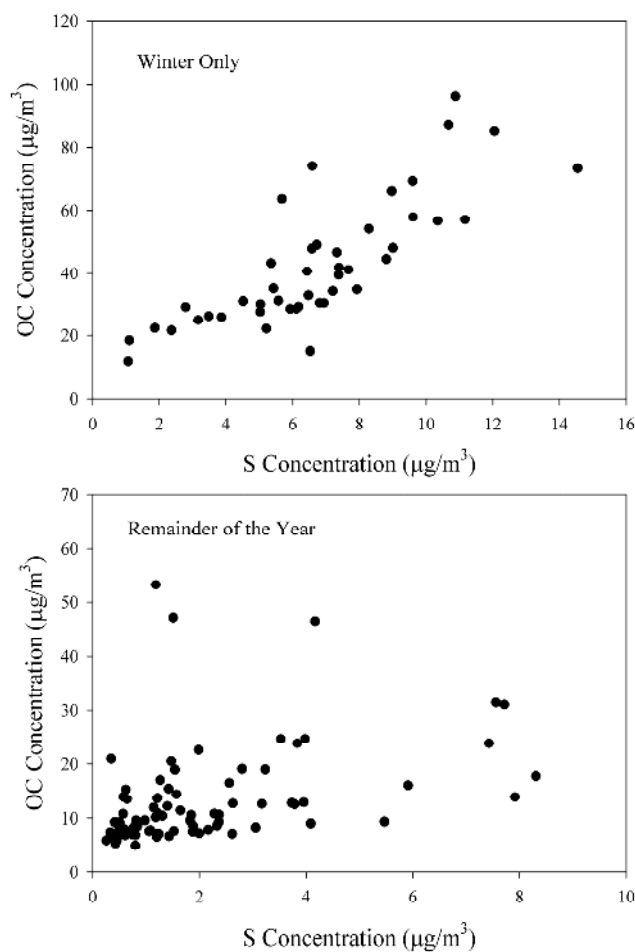**Fig. 6.** OC/BC ratio plotted against wind speed.

Fig. 7. OC plotted against S for the winter period (November to February) (top) and the remainder of the year (bottom).

Fig. 8. Plot of BC against particulate sulfur concentrations for the winter period (November to February) (top) and the remainder of the year (bottom).

winter, there are relatively low temperatures and reduced mixing heights so ground level emissions tend to produce higher concentrations and relatively strong correlations between OC and S. There is a weaker correlation with BC suggesting multiple sources (Fig. 8). During the rest of the year, the strong correlation observed in winter disappears and at times the OC and S are decoupled. High S, OC, and BC concentrations may come from local traffic and/or long range transport (Begum *et al.*, 2011c).
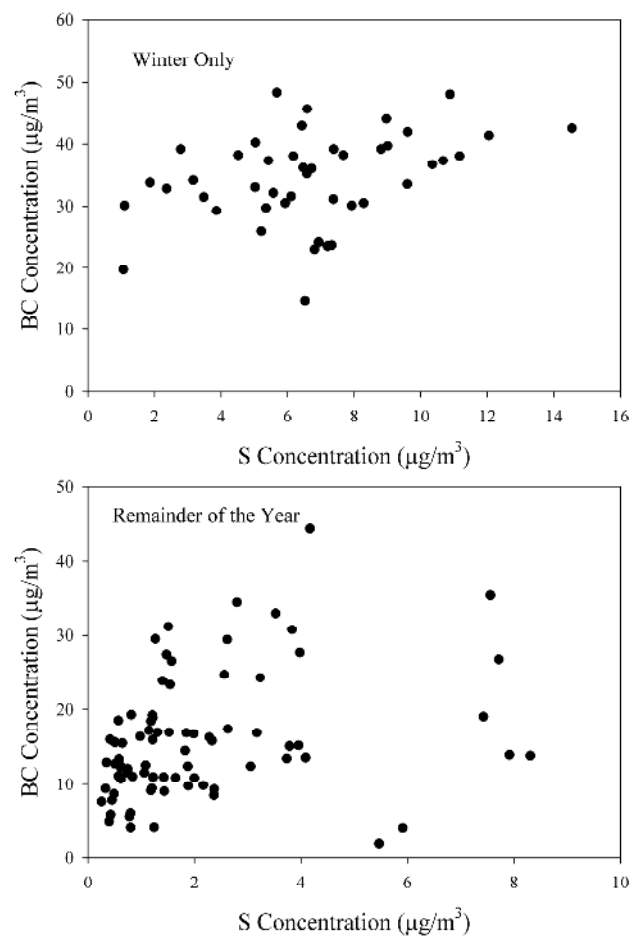
Previous studies showed that back trajectory provided evidence of long-range transport of $PM_{2.5}$ and BC (Begum *et al.*, 2009). The Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT 4) model (Draxler and Rolph, 2003) was used to calculated the air mass backward trajectories for days with high impacts of fine particles. Backward trajectories starting at height of 500 m above the ground level were computed using the vertical mixing

model. A starting height of 500 m has been used elsewhere (Cheng *et al.*, 1993). This height is approximately the height of the mixing layer and has generally found as useful height for such analyses (Zeng and Hopke, 1989). This height was chosen to diminish the effects of surface friction and to represent winds in the lower boundary layer. The fine PM has ability to travel long distance (Begum *et al.*, 2010), therefore the following days were selected to calculate the backwards trajectories using HYSPLIT 4. Archived REANALYSIS meteorological data were used as input. The latitude/longitude of Dhaka was used and trajectories were computed backward in time up to 120 hours (5 days). Tick marks on the trajectory plots indicate 6-hour movement locations.

To explore the role of long range transport for the samples presented in the present work, additional back trajectories have been calculated and are presented in Fig. 9. The green trajectories were calculated for the samples with the highest concentrations (> mean + 2 std; 7 Feb 2010, 23 Jan 2010, 15 Dec 2010 and 8 Feb 2010). The red trajectories were for the samples having concentration near the median value (10 Apr 2010, 25 Oct 2010). The yellow trajectories were for the samples with the lowest concentration (17 Aug 2010). The green trajectories clearly pass through Northern India where there are a number of coal-fired power plants as well as substantial agricultural burning. Thus, these results suggest that transported pollutants did contribute to the worst air quality days. However, it is not possible to quantitatively separate the increment of transported material from that locally emitted. Further studies outside of a major urban area will be required to properly quantify the extent of transported material during the winter period.

Estimated Secondary Organic Carbon Concentrations

Since the BC concentration showed dependency on the wind direction (Begum *et al.*, 2011c) and temperature, it might be concluded that the dominant sources of BC are local. The low OC/BC ratio is then attributed to local emissions: traffic, biomass burning or brick kilns. Based on these observation OCsec has been calculated using $OC/BC_{prim} = 0.98$ and is plotted as a function of time in Fig. 10. The secondary organic carbon (OC_{sec}) provides a significant contribution to the total fine OC during all seasons (Table 1). In calculating SOA, the relation SOA = $1.6 \times OC_{sec}$ was used. Daily average OC_{sec} concentrations in $PM_{2.5}$ varied from 0.47 to 27.1 $\mu gC/m^3$ with an annual average of 4.61 ± 5.26 $\mu gC/m^3$. The annual average contribution of OC_{sec} to the total OC in $PM_{2.5}$ was $41 \pm 17\%$ and the annual average contribution of SOA to the total $PM_{2.5}$ mass was $19 \pm 10\%$. Shakya *et al.* (2010) found that the mean estimated wintertime SOC contribution to OC in Kathmandu was 31%.

CONCLUSIONS

The measurements of organic (OC) and black carbon (BC) in $PM_{2.5}$ were made during February 2010 to February 2011 at an urban, traffic influenced site (Farm Gate) in Dhaka using Air Metrics samplers. Other measured variables are $PM_{2.5}$ mass, sulfur concentrations, and basic meteorological data. A good picture on several quantities associated with OC and BC could be obtained, including daily and seasonal variation of their concentrations, their distribution to the total $PM_{2.5}$ mass and their relation to the meteorology.

Daily average OC and BC concentrations were higher than the literature reports for urban environments. The concentrations of OC and BC relative to the total $PM_{2.5}$ are
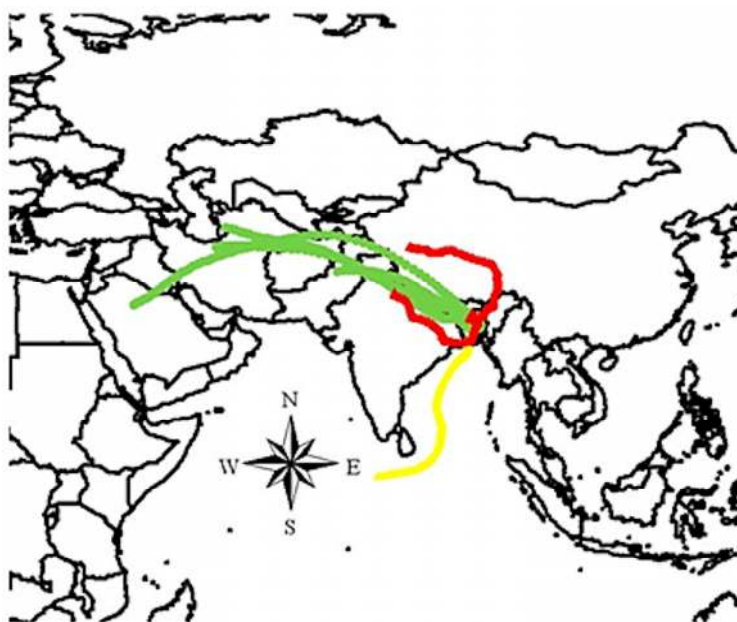

Fig. 9. Back trajectories for selected sampling days. Green lines: High concentrations (≥ mean + 2 std), 7 Feb, 23 Jan 2010 & 15 Dec and 8 Feb 2010; Red lines: Concentrations ~median value, 10 Apr & 25 Oct 2010; Yellow line: Minimum concentration, 17 Aug 2010.
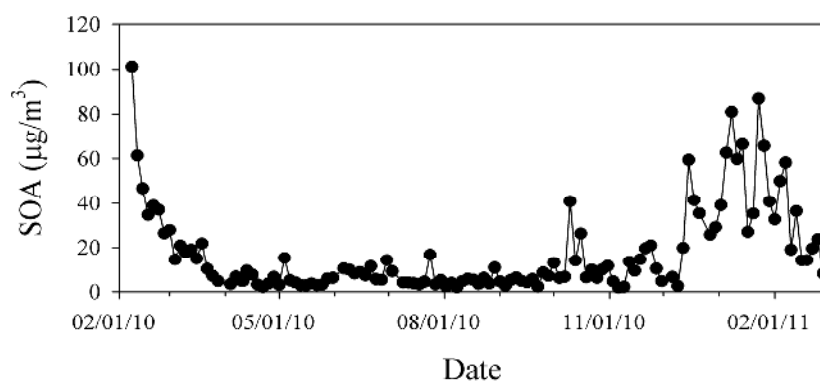
Fig. 10. Time series of the estimated contribution of SOA to the measured OC concentrations.

Table 2. Monthly mean concentrations ($\mu g/m^3$) of OC and BC, $PM_{2.5}$ and Temperature (avg. T).

Month	OC	BC	$PM_{2.5}$	Mean Temp. (°C)
February 2010	50.7 ± 24.8	34.2 ± 10.2	156 ± 56	22.3 ± 1.9
March 2010	20.3 ± 13.0	20.2 ± 12.4	67.0 ± 39.4	28.2 ± 1.3
April 2010	9.8 ± 2.4	13.0 ± 3.4	35.4 ± 9.9	30.4 ± 1.1
May 2010	9.0 ± 2.8	14.0 ± 6.8	40.3 ± 21.2	29.7 ± 1.6
June 2010	9.8 ± 2.0	11.3 ± 4.8	25.8 ± 7.5	29.3 ± 1.7
July 2010	8.1 ± 2.6	11.2 ± 3.6	20.6 ± 5.4	29.7 ± 0.9
August 2010	9.3 ± 2.7	14.6 ± 5.0	25.6 ± 10.5	29.5 ± 0.7
September 2010	10.2 ± 3.9	14.1 ± 7.5	32.6 ± 18.4	28.9 ± 1.0
October 2010	21.0 ± 10.0	25.7 ± 7.2	64.4 ± 23.2	28.3 ± 1.8
November 2010	28.1 ± 7.5	34.6 ± 4.0	124 ± 53	24.9 ± 1.5
December 2010	34.7 ± 13.5	33.3 ± 6.1	151 ± 52	20.1 ± 1.8
January 2011	61.6 ± 17.7	35.9 ± 8.1	221 ± 67	19.0 ± 1.9
February 2011	37.5 ± 16.1	34.0 ± 8.8	150 ± 43	22.7 ± 1.5

also high and have good correlation with wind speed and temperature. The OC/BC ratio correlated with wind speed, temperature and sulfur concentration. Based on these relationships, we concluded that the dominant sources of BC at this site are both local and regional. The local sources are traffic, coal and biomass burning. We also derived estimation for the OC/BC ratio representing the primary traffic-emitted aerosol. Using the ratio (OC/BC) = 0.98, the concentration of OCsec and the contribution of SOA to the $PM_{2.5}$ mass were calculated.

REFERENCES

Baldauf, R.W., Lane, D.D. and Marotz, G.A. (2001). Ambient Air Quality Monitoring Network Design for Assessing Human Health Impacts from Exposures to Airborne Contaminants. *Environ. Monit. Assess.* 66: 63–76.

Begum, B.A., Biswas, S.K., Kim, E., Hopke, P.K. and Khaliquzzaman, M. (2005). Investigation of Sources of Atmospheric Aerosol at a Hot Spot Area in Dhaka, Bangladesh. *J. Air Waste Manage. Assoc.* 55: 227–240.

Begum, B.A., Akhter, S., Sarker, L. and Biswas, S.K. (2006). Gravimetric analysis of Air Filters and Quality Assurance in Weighing. *Nucl. Sci. Appl.* 15: 36–41.

Begum, B.A., Biswas, S.K. and 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.

Begum, B.A., Biswas, S.K. and Hopke, P.K. (2009). Identification of Potential Source Regions of PMF-Modeled Sources of $PM_{2.2}$ in Dhaka, Bangladesh, 28th Annual Conference, Minneapolis, MN, 2009, American Association for Aerosol Research.

Begum, B.A., Biswas, S.K., Markwics, A. and Hopke, P.K. (2010). Identification of Sources of Fine and Coarse Particulate Matter in Dhaka, Bangladesh. *Aerosol Air Qual. Res.* 10: 345–353.

Begum, B.A., Hossain, A., Saroar, G., Biswas, S.K., Nasiruddin, M., Nahar, N., Chowdury, Z. and Hopke, P.K. (2011a). Sources of Carbonaceous Materials in the Airborne Particulate Matter of Dhaka. *Asian J. Atmos. Environ.* 5–4:237–246.

Begum, B.A., Biswas, S.K. and Hopke, P.K. (2011b). Key Issues in Controlling Air Pollutants in Dhaka, Bangladesh. *Atmos. Environ.* 45: 7705–7713.

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. and Hopke, P.K. (2011c). Long Range Transport of Soil Dust and Smoke Pollution in the South Asian Region. *Atmos. Pollut. Res.* 2: 151–157.

Biswas, S.K., Tarafdar, S.A., Islam, A., Khaliquzzaman, M., Tervahattu, H. and 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.

Bond, T.C., Zarzycki, C., Flanner, M.G. and Koch, D.M. (2011) Quantifying Immediate Radiative Forcing by Black Carbon and Organic Matter with the Specific Forcing Pulse. *Atmos. Chem. Phys.* 11: 1505–1525.

Cachier, H., Ducret, J., Bremond, M.P., Youbue, V., Lacaux, J.P., Gaudichet, A. and Baudet, J. (1991). Biomass Burning Aerosols in a Savanna Region of the Ivory Coast in Global Biomass Burning, Levine, J.S. (Ed.). MIT press, Cambridge, MA. p. 174–180.

Cachier, H., Liousse, C., Buat-Menard, P. and Gaudichet, A. (1995). Particulate Content of Savanna Fire Emissions. *J. Atmos. Chem.* 22: 123–148.

Castro, L.M., Pio, C.A., Harrison, R.M. and Smith, D.J.T. (1999). Carbonaceous Aerosol in Urban and Rural European Atmospheres Estimation of Secondary Organic Carbon Concentration. *Atmos. Environ.* 33: 2771–2781.

Cheng, M.D., Hopke, P.K., Barrie, L., Rippe, A., Olson, M. and Landsberger, S. (1993). Qualitative Determination of Source Regions of Aerosol in Canadian High Arctic. *Environ. Sci. Technol.* 27: 2063–2071.

Chow, J.C., Watson, J.G., Prichett, L.C., Pierson, W.R., Frazier, C.A. and Purcell, R.G. (1993). The DRI Thermal/ Optical Reflectance Carbon Analysis System: Description, Evaluation and Applications in U.S. Air Quality Studies. *Atmos. Environ.* 27: 1185–1201.

Chow, J.C., Watson, J.G., Lowenthal, D.H. and Magliano, K.L. (2008). Size-Resolved Aerosol Chemical Concentrations at Rural and Urban Sites in Central California, USA. *Atmos. Res.* 90: 243–252.

Cohen, D.D., Graham, M., Bailey, M. and Kondepudi, R. (1996). Elemental Analysis by PIXE and Other IBA Techniques and Their Application to Source Fingerprinting of Atmospheric Fine Particle Pollution. *Nucl. Instrum. Methods Phys. Res., Sect. B* 109: 218–226.

Corrigan, C.E. and Novakov, T. (1999). Cloud Condensation Nucleus Activity of Organic Compounds: A Laboratory Study. *Atmos. Environ.* 33: 2661–2668.

Dachs, J. and Eisenreich, S.J. (2000). Adsorption onto Aerosol Soot Carbon Dominates Gas-Particle Partitioning of Polycyclic Aromatic Hydrocarbons. *Environ. Sci. Technol.* 34: 3690–3697.

Decesari, S., Facchini, M.C., Fuzzi, S. and Tagliavini, E. (2000). Characterization of Water-Soluble Organic Compounds in Atmospheric Aerosol: A New Approach. *J. Geophys. Res.* 105: 1481–1489.

Draxler, R.R. and Rolph, G.D. (2003). HYSPLIT 4(Hybrid Single-Particle Lagrangian Integrated Trajectory) Model Access via NOAA ARL READY Website (http://www.arl.noaa.gov/ready/hysplit4.html), NOAA Air Resources Laboratory, Silver Spring, MD.

Grgic, I., Dovzan, A., Bercic, G. and Hudnik, V. (1998). The Effect of Atmospheric Organic Compounds on the Fe-catalyzed S(IV) Autooxidation in Aqueous Solution. *J. Atmos. Chem.* 29: 315–337.

Hildemann, L.M., Markowski, G.R. and Cass, G.R. (1991). Chemical Composition of Emissions from Urban Sources of Fine Organic Aerosol. *Environ. Sci. Technol.* 25: 744–

759.

Hitzenberger, R. and Tohno, S. (2001). Comparison of Black Carbon (BC) Aerosols in Two Urban Areas - Concentrations and Size Distributions. *Atmos. Environ.* 35: 2153–2167.

Jacobson, M.Z. (2001). Strong Radiative Heating Due to the Mixing State of Black Carbon in Atmospheric Aerosols. *Nature* 409: 672–695.

Kehrwald, N.M., Thompson, L.G., Yao, T.D., Mosley-Thompson, E., Schotterer, U., Alfimov, V., Beer, J., Eikenberg, J. and Davis, M.E. (2008). Mass Loss on Himalayan Glacier Endangers Water Reseurces. *Geophys. Res. Lett.* 35: L22502, doi: 10.1029/2008GL035556.

Landsberger, S. and Creatchman, M. (1998). *Elemental Analysis of Airborne Particles*, Boca Raton, FL: CRC Press, Inc.

Lary, D.J., Shallcross, D.E. and Toumi, R. (1999). Carbonaceous Aerosols and Their Potential Role in Atmospheric Chemistry. *J. Geophys. Res.* 104: 15929–15940.

Lin, J.J. and Tai, H.S. (2001). Concentrations and Distributions of Carbonaceous Species in Ambient Particles in Kaohsiung City, Taiwan. *Atmos. Environ.* 35: 2627–2636.

Malm, W.C. and Day, D.E. (2000). Optical Properties of Aerosols at Grand Canyon National Park. *Atmos. Environ.* 34:3373–3391.

Maxwell, J.A., Campbell, J.L. and Teesdale, W.J. (1989). The Guelph PIXE Software Package. *Nucl. Instrum. Methods Phys. Res., Sect. B* 43:218–230.

Maxwell, J.A., Teesdale, W.J. and Campbell, J.L. (1995). The Guelph PIXE Software Package II. *Nucl. Instrum. Methods Phys. Res., Sect. B* 95: 407–421.

Ruellan, S. and Cachier, H. (2001). Characterization of Fresh Particulate Vehicular Exhausts near a Paris High Flow Road. *Atmos. Environ.* 35; 453–468.

Salako, G.O., Hopke, P.K., Cohen, D.D., Begum, B.A., Biswas, S.K., Pandit, G.G., Chung, Y.S., Rahman, S.A., Hamzah, M.S., Davy, P., Markwitz, A., Shagjjamba, D., Lodoysamba, S., Wimolwattanapun, W. and Bunprapob, S. (2012). Exploring the Variation between EC and BC in a Variety of Locations. *Aerosol Air Qual. Res.* 12: 1–7.

Salam, A., Bauer, H., Kassin, K., Ullah, S.M. and Puxbaum, H. (2003). Aerosol Chemical Characteristics of a Mega-City in Southeast Asia (Dhaka, Bangladesh). *Atmos. Environ.* 37; 2517–2528.

Shakya, K.M., Ziemba, L.D. and Griffin, R.J. (2010). Characteristics and Sources of Carboneceous, Ionic and Isotopic Species of Wintertime Atmospheric Aerosols in Kathmandu Valley, Nepal. *Aerosol Air Qual. Res.* 10: 219–230.

Tegen, I., Hollrig, P., Chin, M., Fung, I., Jacob, D. and Penner, J. (1997). Contribution of Different Aerosol Species to the Global Aerosol Extinction Optical Thickness: Estimates from Model Results. *J. Geophys. Res.* 102: 23895–23915.

Turpin, B.J. and Lim, H.J. (2001). Species Contributions to $PM_{2.5}$ Mass Concentrations: Revisiting Common Assumptions for Estimating Organic Mass. *Aerosol Sci.*

Technol. 35: 602–610.

Viidanoja, J., Kerminen, V.M. and Hillamo, R. (2002). Measuring the Size Distribution of Atmospheric Organic and Black Carbon Using Impactor Sampling Coupled with Thermal Carbon Analysis: Method Development and Uncertainties. *Aerosol Sci. Technol.* 36: 607–616.

Viidanoja, J., Sillanpaa, M., Laakia, J., Kerminen, V.M., Hillamo, R., Aarnio, P. and Koskentalo, T. (2002). Organic and Black Carbon in $PM_{2.5}$ and PM_{10}: 1 Year of Data

from an Urban Site in Helsinki, Finland. *Atmos. Environ.* 36: 3183–3193.

Zeng, Y. and Hopke, P.K. (1989). A Study on the Sources of Acid Precipitation in Ontario, Canada. *Atmos. Environ.* 23: 1499–1509.