

# Characteristics of atmospheric trace gases, particulate matter, and heavy metal pollution in Dhaka, Bangladesh

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**Abstract** Aerosol particulate matter (PM<sub>10</sub> and PM<sub>2.5</sub>) and trace gases (SO<sub>2</sub>, NO<sub>2</sub>, CO and O<sub>3</sub>) were sampled at five locations in greater Dhaka, Bangladesh, between January and April 2006. Particulate matter was collected on micro-fiber filters with a low-volume sampler, and trace gases (SO<sub>2</sub>, NO<sub>2</sub>, and O<sub>3</sub>) were collected with an impinger equipped with PM samplers. Carbon monoxide was determined using the Indicator Tube method. The total average concentrations of SO<sub>2</sub>, NO<sub>2</sub>, CO, and O<sub>3</sub> were 48.3, 21.0, 166.0 and 28 μg m<sup>-3</sup>, respectively. The total average concentrations of SO<sub>2</sub> and NO<sub>2</sub> were much lower than the annual average guideline values of the World Health Organization (WHO). The total average O<sub>3</sub> concentration was also much lower than the daily maximum values established by WHO (average of 100 μg m<sup>-3</sup> for an 8-h sample). The total average concentrations of five sites were 263, 75.5 and 66.2 μg m<sup>-3</sup> for SPM, PM<sub>10</sub> and PM<sub>2.5</sub>, respectively. The mass of PM<sub>2.5</sub> is approximately 88% of the PM<sub>10</sub> mass, indicating that fossil fuel is the main source of PM in Dhaka. An atomic absorption spectrophotometer was used to determine the heavy metal concentrations in the PM<sub>2.5</sub> size fraction. The total average concentrations of As, Cd, Cu, Fe, Pb, and Zn in PM<sub>2.5</sub> were 6.3, 13, 94, 433, 204, and 381 ng m<sup>-3</sup>, respectively. The Pb concentration in Dhaka shows a decreasing tendency, presumably due to the ban on the use of leaded fuel. The overall trace metal concentrations in Dhaka are higher than those in European (e.g., Spain, Norway) and East Asian (e.g., Taiwan) locations, but lower than those measured in Southeast

Asian (Kanpur, Delhi, Mumbai, India; Lahore, Pakistan) cities.

**Keywords** Air pollution · Heavy metals · Particulate matter · Trace gases

## Introduction

Air pollution has a great impact on human health, climate change, agriculture, and the natural ecosystem (Decker et al. 2000; Mayer et al. 2000; Molina and Molina 2004; Molina et al. 2004). The modernization and industrialization of developing countries has led to the increased use of fossil fuels and their derivatives. As such, developing countries are confronted with the great challenge of controlling the atmospheric pollution, especially in the rapidly growing megacities. Concern about air pollution in urban regions is receiving increasingly importance worldwide, especially pollution by gaseous and particulate trace metals (Azad and Kitada 1998; Salam et al. 2003; Begum et al. 2004; and Cachier et al. 2005).

Gaseous pollutants have major negative impacts on health. They also play an important role in environmental changes and changes in atmospheric chemistry. SO<sub>2</sub> and NO<sub>2</sub> form acids through different chemical reactions in the atmosphere, and these acids are subsequently deposited on land and ocean surfaces as acid rain. It is anticipated that the increasing load of atmospheric sulfur dioxide (SO<sub>2</sub>), nitrogen dioxide (NO<sub>2</sub>), carbon monoxide (CO), and ozone (O<sub>3</sub>) will contribute to global climate change; consequently, it is necessary to quantify the emissions in the very near future.

A great deal of attention has focused on particulate matter (PM) pollution due to their severe health effects,

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especially fine particles. Several epidemiological studies have indicated a strong association between elevated concentrations of inhalable particles ( $PM_{10}$  and  $PM_{2.5}$ ) and increased mortality and morbidity (Perez and Reyes 2002; Lin and Lee 2004; Namdeo and Bell 2005). Particulate matter pollution in the atmosphere primarily consists of micron and sub-micron particles from anthropogenic (motor vehicles, biomass, fossil fuel burning) and natural sources (windblown soils and sea spray) (Cohen 1998). The characterization of fine particles has become an important priority of governments, regulators, and researchers due to their potential impact on health, climate, global warming, and long-range transport (Dockery et al. 1993; IPCC 2001).

Dhaka, Bangladesh, is one of the densely populated megacities in the world, with about 15 million inhabitants within a 300-km<sup>2</sup> area. Dhaka also suffers from major traffic congestion from both public and private sources. A high concentration of air pollutants, such as black carbon, has already been reported in Dhaka (Salam et al. 2003; Begum et al. 2004). Vehicular emissions, biomass burning for cooking, brick kilns, and construction activities in and around the city are the main contributors to aerosol pollution in Dhaka (Azad and Kitada 1998).

Here, we report the occurrence and characteristics of gaseous ( $SO_2$ ,  $NO_2$ ,  $CO$  and  $O_3$ ) pollutants, particulate matter [suspended (S)PM,  $PM_{10}$  and  $PM_{2.5}$ ], and heavy metal concentrations [arsenic (As), cadmium (Cd), copper (Cu), iron (Fe), lead (Pb), and zinc (Zn)] from January to April, 2006 at five locations in the greater Dhaka area.

## Sampling and experimental methods

### Sampling locations in Dhaka, Bangladesh

Bangladesh is situated in the eastern part of South Asia. It is surrounded by India on the west, the north, and the northeast, Myanmar on the southeast, and the Bay of Bengal on the south (Fig. 1). Dhaka (23°76'N, 90°38'E, 8 m a.s.l.) is the capital of Bangladesh. It is also the center of commerce and industries of Bangladesh and is growing rapidly—together with all the problems associated with a megacity. Dhaka is situated in flat land surrounded by rivers (Fig. 1). The five sampling locations were selected to reflect the influences from industrial, commercial, residential, and heavy traffic sources in the highly populated greater Dhaka area: Tower Bhaban (Dhaka University campus), Medinova hospital (Dhanmondi), Noverties Pharmaceuticals (Tejgaon), BCIC Bhaban (Motijheel), and Jahangirnagar University campus (Savar). The Jahangirnagar University (JU) campus site is about 30 km northwest of Dhaka city center and considered to be an urban

background site. The name of the sampling sites and their characteristics are given in Table 1.

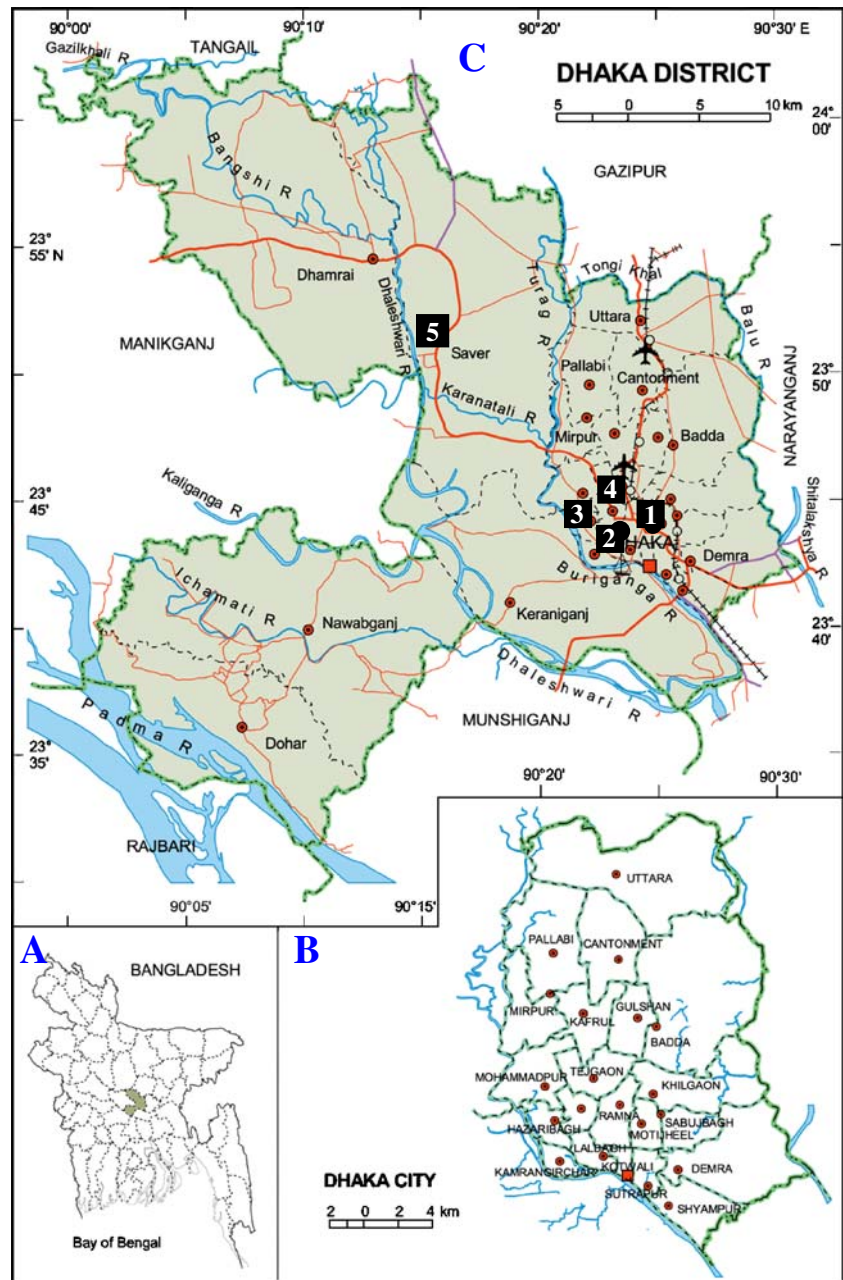
### Meteorology of Dhaka, Bangladesh

The climate of Bangladesh is characterized by high temperatures, excessive humidity, and distinctly marked seasonal variations in precipitation. Bangladesh can be divided into four seasons: pre-monsoon (March–May), monsoon (June–September), post-monsoon (October–November), and winter (December–February). The average meteorological conditions of Dhaka city during the different seasons have been reported by Salam et al. (2003) and Begum et al. (2004). The average winter temperature varies between 9 and 25°C, and the average summer temperature varies from 24 to 34°C. The highest relative humidity occurs in July, reaching 99%, and the lowest occur in December, when it is 36%. Moderately higher temperatures are generally observed during the afternoon. Light precipitation occurs during March and April. The average wind velocity during the sampling period at Dhaka was 1.20 m s<sup>-1</sup> (source: Bangladesh Meteorological Department). Backward air trajectory studies (NOAA/ARL 2005) indicated that air masses were transported from north to southeast (January and February) and also south or southwest to north or northwest (March and April).

### Particulate matter and trace gas sampling

Particulate matter and trace gas samplings were performed between January and April 2006 at five locations in Dhaka, Bangladesh (Table 1) using a respirable dust sampler (model 460 NL; Enviro-Tech, Rancho Cordova, CA) for  $PM_{10}$ , a fine particulate sampler (model APM 550; Enviro-Tech) for  $PM_{2.5}$ , and an organic vapor sampler (model APM 850; Enviro-Tech) for  $CO$  measurements with the Indicator Tube method. The PM sampler (model 460 NL; Enviro-Tech) was equipped with impingers to collect the gaseous gases ( $SO_2$ ,  $NO_2$ , and  $O_3$ ). Ambient air laden with suspended particulates enters the respirable dust sampler through an inlet pipe. As the air enters the cyclone, coarse, non-respirable dust is separated from the air by centrifugal forces acting on the solid particles. These coarse particulates fall through the cyclone and are collected in the sampling bottle fitted at the bottom. The air stream passing through the glass micro-fiber filter (Whatman, Maidstone, UK; size: 20.3 × 24.4 cm,) paper, which was clamped between the top cover and filter adapter assembly, carries the fine dust forming the respirable fraction ( $PM_{10}$ ). The flow rate of PM collection was determined from the difference of the initial and final flow rate of the instrument gas meter reading. The  $PM_{2.5}$  and  $PM_{10}$  were deposited on

**Fig. 1** a Map of Bangladesh, b Dhaka city map, c map of Dhaka Division showing the location of the sampling sites. Numbers on black solid square refer the sampling sites: 1 BCIC Bhaban, Motijheel, 2 Tower Bhaban, Dhaka University (DU) campus, Ramna, 3 Medinova hospital, Dhanmondi, 4 Noverties Pharmaceutical, Tejgaon, 5 Jahangirnagar University campus



micro-fiber filters (Millipore, Bedford, MA), and those larger than  $PM_{10}$  were collected in the dust Cup Vail. Total SPM was calculated from the sum of the  $PM_{10}$  and  $PM$  larger than  $PM_{10}$ . A regular calibration is necessary to

ensure that the sample collection with both instruments is reliable for  $PM_{10}$  (Enviro-Tech model 460 NL) and  $PM_{2.5}$  (EnviroTech model APM 550). A factory calibration was carried out before setting up the instruments for the field

**Table 1** Description of the sampling locations in the greater Dhaka region, Bangladesh

Name	Location	Status of the sites
Tower Bhaban	Dhaka University (DU) campus	Mainly residential with low traffic
BCIC Bhaban	Motijheel, Dhaka	Commercial area with heavy traffic
Medinova hospital	Dhanmondi, Dhaka	Residential area with medium traffic
Noverties Pharmaceuticals	Tejgaon, Dhaka	Industrial area with heavy traffic
Near administrative building	Jahangirnagar University (JU), Savar	Semi urban area with very low traffic

measurement. It is absolutely necessary to calibrate the instruments once every 6 months if the instruments are operating 2–3 days per week. The calibrations were done directly by the manufacturer (Envirotech Instruments, New Delhi, India). Sampling instruments were set up on a traffic van (mini truck) for collecting gaseous ( $\text{SO}_2$ ,  $\text{NO}_2$ , and  $\text{O}_3$ ) and PM from morning to evening (9:00 a.m. to 5:00 p.m. local time), except for CO. The CO samples were collected for 1 h. The sampling instruments were placed about 3 m above ground level. The collected samples were brought to the Inorganic and Analytical Research laboratory, Department of Chemistry, Dhaka University. Trace gas ( $\text{SO}_2$ ,  $\text{NO}_2$ , CO, and  $\text{O}_3$ ) samples were analyzed immediately. The PM filters were equilibrated for 48 h at a controlled temperature ( $22 \pm 2^\circ\text{C}$ ) and relative humidity ( $55 \pm 5\%$ ) prior to weighing and then stored in the refrigerator for further trace metal analysis.

#### Determination of trace gases

##### *SO<sub>2</sub> determination*

The method for measuring  $\text{SO}_2$  was adapted from West and Gaeke (1956). In this method, air-exposed samples are treated in a solution of potassium tetrachloro-mercurate, and the concentration of  $\text{SO}_2$  can be measured in the range of 20–1050  $\mu\text{g m}^{-3}$ . A dichlorosulphitomercurate complex is formed, which subsequently reacts with pararosaniline and formaldehyde to form the intensely colored pararosaniline methylsulphonic acid (Lyles et al. 1965). We measured the absorbance of the colored solution with an UV-spectrophotometer (model AA-680; Shimadzu, Japan) at 560 nm, and the concentration of  $\text{SO}_2$  was determined based on a calibration curve of five standard solutions (0.0, 4.155, 8.29, 16.0, 24.87, and 33.16  $\mu\text{g SO}_2/25$  ml). A blank sample was prepared using the same procedure as that for the air-exposed sample for the blank correction.

##### *NO<sub>2</sub> determination*

The principle of  $\text{NO}_2$  measurement in atmospheric samples was described by Jacob and Hochheiser (1958); the normal range of this method is 9–750  $\mu\text{g m}^{-3}$ . In this method, air-exposed samples were treated with sodium hydrogen and sodium arsenite. The sample solution was again treated with phosphoric acids, sulfanilamide, and a N-(1-naphthyl)-ethylenediamine di-hydrochloride (NEDA) solution. A colored solution was produced, and the absorbance of the colored solution was measured with a UV-spectrophotometer (model AA-680I Shimadzu) at 540 nm. The concentrations of  $\text{NO}_2$  were determined from the calibration curve of five standard solutions (0.0, 1.0, 2.0, 3.0, 5.0, 7.0, and 9.0  $\mu\text{g NO}_2/50$  ml). A blank sample was also prepared using the

same procedure as that for the air-exposed sample for the blank correction.

##### *CO determination*

The concentration of CO was determined by Indicator Tube Method. The air was passed through the tube by an aspirator. After 1 h of sampling, the color of the fixed portion of the tube was matched with given chart value (APM 850 model; Enviro-Tech, India). The concentration was calculated using the equations: CO concentration ( $\mu\text{gm}^{-3}$ ) = [(Chart value of 1 Squeeze  $\times 0.75 \times 10^6$ )/F], where 0.75 is the factor for the density of CO,  $10^6$  is the conversion factor for both air volume (from liter to cubic meter) and milligram to microgram, and F is the total volume for air passed (l) through the indicator tube. The total volume of air passed through the CO indicator tube = average flow rate (lpm)  $\times$  time (min).

##### *O<sub>3</sub> determination*

An absorbing reagent was prepared with  $\text{KH}_2\text{PO}_4$ ,  $\text{Na}_2\text{HPO}_4$ , and KI for  $\text{O}_3$  concentration determination. The air-exposed samples were treated with the absorbing reagents, which produced a colored solution. The absorbance of the colored solutions was measured at 352 nm against a blank using a UV-spectrophotometer (model AA-680; Shimadzu). The concentration of  $\text{O}_3$  was measured from a calibration curve of five standard solutions (0.0, 1.0, 3.0, 5.0, 7.0, and 9.0  $\mu\text{g}/25$  ml). Blank correction was performed by preparing a blank sample using the same procedure as that used for the air-exposed samples.

#### Determination of PM

The aerosol masses for  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  were determined by weighing the filters before and after exposure at ambient temperature and atmospheric pressure with an OHAUS analytical balance (model no. AR1140; OHAUS, Pine Brook, NJ). Total suspended particulate (TSP) matter was determined from the sum of  $\text{PM}_{10}$  and particles larger than  $\text{PM}_{10}$ . The mass of PM larger than  $\text{PM}_{10}$  was determined from the initial and final weight of the dust Cup Vail. Samples were transported from the sampling site to the laboratory and kept them in a refrigerator until analysis to minimize volatilization. Blank correction was performed by preparing field blanks using the same procedure as that for the PM samples.

#### Determination of heavy metals

An atomic absorption spectrophotometer (AAS; model AA-680; Shimadzu) was used to determine the concentrations

of heavy metals (As, Cd, Cu, Fe, Pb, Zn) in the PM<sub>2.5</sub> size fraction during the period January–April 2006. The PM<sub>2.5</sub>-loaded filters were extracted in an acid mixture to remove heavy metals. Each filter (diameter 4.7 cm) was placed in 30 ml concentrated nitric acid (70%) and 10 ml hydrogen peroxide (30%) solution in a digestion vessel. The digestion vessels were placed on a sand bath and heated to 180°C for about 1 h until the acid solution had evaporated. The procedure was repeated twice and was continued until the residue was almost dry. Upon cooling, 60 ml water was added and agitated carefully. The solution was filtered into a 100-ml volumetric flask, diluted to the mark with de-ionized water, and used for the trace metal analysis with AAS. One unexposed filter was prepared as a blank using the same procedure as that followed for the air-exposed filter.

For the determination of the heavy metal concentrations, calibration curves for each metal were prepared with five standard solutions at different concentrations. Metal solutions were aspirated into the flame of the AAS, where ions are reduced to the atomic state, and absorbed light can be measured quantitatively at a particular wavelength. However, the concentrations of each metal were determined from the standard calibration curve of the individual metal.

## Results and discussion

### Overview of the experimental results

Assessment of the concentrations of ambient air PM<sub>10</sub> and PM<sub>2.5</sub>, trace gases (SO<sub>2</sub>, NO<sub>2</sub>, CO and O<sub>3</sub>), and heavy metals (As, Cd, Cu, Fe, Pb, Zn) were determined on PM<sub>2.5</sub> size fractions at five locations in Dhaka, Bangladesh from January to April 2006. The sampling sites were located at Tower Bhaban (Dhaka University campus), Medinova hospital (Dhanmondi), Novarties Pharmaceuticals (Tejgaon), BCIC Bhaban (Motijheel), and Jahangirnagar University campus (Savar). The description of the sampling sites are given in Table 1 and also shown in Fig. 1. The concentrations of measured components varied between residential, industrial, and semi-urban sites in the greater Dhaka area and also varied slightly temporally between January and April 2006. The concentrations of trace gases remained almost constant over the entire sampling period, whereas those of the PM varied from 1 month to the other, with higher concentrations of both PM<sub>10</sub> and PM<sub>2.5</sub> observed in January and lower concentrations in April. Details of the experimental results were given in Tables 2, 3, 4.

### Trace gases

The atmospheric trace gases (SO<sub>2</sub>, NO<sub>2</sub>, CO and O<sub>3</sub>) were measured at five locations in Dhaka during the period of

January to April, 2006. Samples were collected once in a week at each location. The sampling time was 8 h for SO<sub>2</sub>, NO<sub>2</sub>, and O<sub>3</sub> and 1 h for CO. The samples were collected in an impinger attached to the PM samplers for SO<sub>2</sub>, NO<sub>2</sub>, and O<sub>3</sub>, and an organic vapor sampler was used for CO measurements with the Indicator Tube method. The overall average value of SO<sub>2</sub> at five sampling locations in Dhaka was 48 µg m<sup>-3</sup>, which is very close to the annual average of the World Health Organization's (WHO) guideline values for the European Union (WHO 2000: 50 µg m<sup>-3</sup>). Because the total sampling period in our study was about 4 months [8 h daily for all gases except CO (1 h)] and extended from the winter through the beginning of the monsoon season, it can be considered to be an average for the whole year. The highest concentration (76.8 µg m<sup>-3</sup>) of SO<sub>2</sub> was found in the commercial and heavy traffic areas (BCIC Bhaban, Motijheel), and the lowest concentration (20.7 µg m<sup>-3</sup>) was found in the semi-urban area (Jahangirnagar University campus, Savar). The elevated concentration of SO<sub>2</sub> in the city center is probably due to the high content of sulfur in fossil fuel. Azad and Kitada (1998) reported that the primary source of SO<sub>2</sub> in Dhaka is traffic fuels (55.8%) followed by brick fields (28.8%), industry (10.5%), and others (about 5%); they also reported high SO<sub>2</sub> concentrations in the southern industrial area, where the highest value was about 286 µg m<sup>-3</sup>.

The total average concentration of NO<sub>2</sub> at five locations in Dhaka was 21.0 µg m<sup>-3</sup>, which is about half of the annual WHO guideline value 2005 (40 µg m<sup>-3</sup>). The NO<sub>2</sub> enters the atmosphere from various natural and anthropogenic sources, including lighting, action of microorganisms on nitrogen-based fertilizer, but the most important and major anthropogenic source is the combustion of fossil fuel in traffic. The highest concentration of NO<sub>2</sub> (40 µg m<sup>-3</sup>) was found at Medinava hospital, Dhanmondi site, with medium traffic, whereas the lowest concentration (5.0 µg m<sup>-3</sup>) was found at Jahangirnagar University, Savar, a semi-urban location. Azad and Kitada 1998 measured NO<sub>2</sub> concentrations with molecular diffusion tubes in Dhaka, Bangladesh. They reported that the highest 10-day average was about 65.8 µg m<sup>-3</sup>, with higher concentrations appearing in the city center along the main roads of Dhaka. Motor vehicles and brick fields were speculated to be the two major emission sources in Dhaka.

The measured CO values varied between industrial, urban, and semi-urban sites. The highest concentration (334 µg m<sup>-3</sup>) of CO was observed at the industrial site (Novarties, Tejgaon), whereas the lowest value (42 µg m<sup>-3</sup>) was found in the semi-urban area (Jahangirnagar University, Savar). The highest concentration of CO at the industrial sites is presumably due to the incomplete conversion of fossil fuel during different mechanical and industrial processes. However, the overall (4 months at five sampling

**Table 2** Concentrations of atmospheric trace gases at five different locations in greater Dhaka, Bangladesh

Sampling Location	SO <sub>2</sub>	NO <sub>2</sub>	CO	O <sub>3</sub>
Tower Bhaban, Dhaka university	30.5 (±7)	25.0 (±5)	90.8 (±9)	9.81(±3)
BCIC Bhaban, Motijheel	76.8 (±11)	10.3 (±3)	238.2 (±14)	19.6 (±7)
Medinova hospital, Dhanmondi R/A	49.1 (±5)	40.5 (±8)	125 (±12)	29.4 (±13)
Novarties Pharmaceuticals, Tejgaon	64.3 (±15)	23.6 (±5)	334.2 (±22)	3.92 (±2)
Jahangirnagar University, Savar	20.7 (±6)	5.53 (±2)	41.7 (±5)	76.5 (±18)
Average ( <i>n</i> =75)	48.3	21.0	166.0	27.9

Units are in  $\mu\text{g m}^{-3}$

Samples were collected once a week at each location (each location has a total of 15 samples). Sampling time was 8 h for SO<sub>2</sub>, NO<sub>2</sub>, and O<sub>3</sub>, and 1 h for CO

locations) average value of CO in Dhaka was  $166 \mu\text{g m}^{-3}$  (1-h sampling time daily).

The total average concentration of O<sub>3</sub> at five sampling sites in Dhaka was  $28 \mu\text{g m}^{-3}$ , which is much lower than the daily maximum value ( $100 \mu\text{g m}^{-3}$ ; WHO 2005). However, O<sub>3</sub> is one of the most ubiquitous and toxic pollutants found in ambient air. A higher concentration ( $76.5 \mu\text{g m}^{-3}$ ) of O<sub>3</sub> was found in the semi-urban area (Jahangirnagar University campus, Savar), and the lowest concentration ( $3.92 \mu\text{g m}^{-3}$ ) was found in the industrial area (Novarties, Tejgaon).

#### Particulate matter

Atmospheric particulate matter (PM<sub>10</sub>, PM<sub>2.5</sub>) was collected on micro-fiber filters with low-volume samplers from 9:00 A.M. to 5:00 P.M. (8 h on average) between January and April 2006 at five locations in Dhaka, Bangladesh. Total suspended particulate matter was calculated from the sum of the PM<sub>10</sub> and particles larger than PM<sub>10</sub> (collected in the dust Cup Vail). The total average concentration of SPM in the ambient air of Dhaka was  $262.6 \mu\text{g m}^{-3}$ . The World Bank and Department of the Environment of Bangladesh found SMP concentrations of  $665\text{--}2456 \mu\text{g m}^{-3}$  at Farmgate, Dhaka (Core 1998) based on 8-h measurements at several locations along busy roads in Dhaka city. The

difference between these 1998 results and those of our study indicates that the ambient concentrations of SPM in Dhaka are decreasing remarkably. However, our measurements showed that the maximum daily average (exposure time: 8 h daily) concentration of SPM was  $570 \mu\text{g m}^{-3}$  at Motijheel in January, 2006. The SPM concentrations among the five sampling sites varied from  $126.2 \mu\text{g m}^{-3}$  at Jahangirnagar University (JU) campus, Savar to  $523.0 \mu\text{g m}^{-3}$  at BCIC Bhaban, Motijheel (Table 3). The causes of the higher SPM values in Dhaka may be road dusts, construction activities, incomplete combustion of fossil fuel from traffic vehicles and brick kilns, and long-range transport (Begum et al. 2004).

The total average concentrations of PM<sub>10</sub> and PM<sub>2.5</sub> were  $75.5$  and  $66.2 \mu\text{g m}^{-3}$ , respectively, at five locations in the greater Dhaka area. At the five sampling locations in Dhaka, the average mass concentrations varied from  $62.0$  to  $91.2 \mu\text{g m}^{-3}$  for PM<sub>10</sub>, whereas these ranged between  $54.2$  and  $80.5 \mu\text{g m}^{-3}$  for PM<sub>2.5</sub> (Table 3). Chuersuwan et al. (2008) reported mass concentrations of  $57.6\text{--}108.1 \mu\text{g m}^{-3}$  for PM<sub>10</sub> and between  $69.0$  and  $37.9 \mu\text{g m}^{-3}$  for PM<sub>2.5</sub> at four sampling sites in Bangkok, Thailand. The PM<sub>10</sub> mass concentrations in Kanpur, India were much higher than those we found for Dhaka. At three sampling locations in Kanpur, the average PM<sub>10</sub> mass concentration was  $211 \mu\text{g m}^{-3}$  and

**Table 3** Concentrations of particulate matter of different size fractions ( $\mu\text{m}$ ) at five different locations in greater Dhaka between January and April 2006

Sampling Sites	SPM	PM <sub>10</sub>	PM <sub>2.5</sub>	PM <sub>2.5-10</sub>	PM <sub>2.5</sub> /PM <sub>10</sub>
Tower Bhaban, DU campus	130.8 (±11)	66.2 (±9)	54.2 (±7)	12.0	0.82
Medinova Hospital, Dhanmondi	386.2 (±20)	73.7 (±16)	63.6 (±8)	10.1	0.86
Novarties Pharmaceuticals, Tejgaon	147 (±10)	91.2 (±5)	80.5 (±9)	10.7	0.88
Jahangirnagar University, Savar	126.2 (±14)	62 (±10)	57.1 (±6)	4.90	0.92
BCIC Bhaban, Motijheel	523 (±29)	84.5 (±7)	75.6 (±13)	8.90	0.89
Average ( <i>n</i> =75)	263	75.5	66.2	9.3	0.88

SPM Suspended Particulate Matter, PM Particulate Matter

Units are in  $\mu\text{g m}^{-3}$

The sampling time was 8 h. Samples were collected once a week for each sampling location (each location has a total of 15 samples)

**Table 4** Concentrations of trace metals at five different sampling sites in greater Dhaka for the size fraction PM<sub>2.5</sub> between January and April 2006

Sampling Location	As	Cd	Cu	Fe	Pb	Zn
Tower Bhaban, DU campus	6.2 (±3)	0.19 (±0.1)	30.9 (±12)	244 (±34)	103 (±44)	426 (±45)
BCIC Bhaban, Motijheel	6.6 (±2)	5.04 (±2)	90.7 (±28)	557 (±43)	335 (±26)	428 (±59)
Medinova hospital, Dhanmondi	4.3 (±2)	11.5 (±3)	132.4 (±45)	469 (±53)	227 (±33)	428 (±58)
Novarties Pharmaceuticals, Tejgaon	7.9 (±3)	34.9 (±9)	92.6 (±60)	669 (±92)	305 (±27)	516 (±35)
Jahangirnagar University, Savar	6.4 (±4)	14.3 (±6)	127.1 (±35)	224 (±50)	51 (±12)	108 (±22)
Total Average ( <i>n</i> =75)	6.28	13.2	95	433	204	381

All units are in ng m<sup>-3</sup>.

The sampling time was 8 h daily. Samples were collected once a week at each sampling location (each location has a total 15 samples)

ranged from 80 to 281 μg m<sup>-3</sup> (Sharma and Maloo 2005). The average PM<sub>2.5</sub> mass concentration at the same locations, 101 μg m<sup>-3</sup>, was also much higher than that at Dhaka, ranging from 65 to 146 μg m<sup>-3</sup> (Sharma and Maloo 2005). The ratio between PM<sub>2.5</sub> and PM<sub>10</sub> in Dhaka shows that particulate mass mostly derived from fine fraction, which is very harmful for human health. PM<sub>2.5</sub> mass is about 88% of that of PM<sub>10</sub>, which indicates that the source of PM is mostly from fossil fuel. Begum et al. 2004 also reported that vehicles normally produce more fine particles (PM<sub>2.5</sub>) than coarse ones (PM<sub>2.5-10</sub>), with the latter mostly originating from mechanical processes. The concentrations of the coarse particles (PM<sub>2.5-10</sub>) varied from 12.0 to 9.31 μg m<sup>-3</sup>, and the average concentration for the coarse fraction was 9.31 μg m<sup>-3</sup> (Table 3). However, the elevated concentrations of PM observed in Dhaka, Bangladesh are still lower than those reported for Southeast Asian sites (Smith et al. 1996; Sharma and Maloo 2005).

#### Heavy metals

The concentrations of selected trace metals were determined at five locations in the greater Dhaka region for PM<sub>2.5</sub> in the period from January to April 2006. PM<sub>2.5</sub> samples were collected on fiber filters (diameter 4.7 cm) with a low-volume sampler. An AAS was used to determine the concentrations of heavy metals (As, Cd, Cu, Fe, Pb, Zn). The measured concentrations of the heavy metals are given in Table 4.

#### Arsenic

Arsenic is a major ground water pollutant in many parts of Bangladesh. Millions of people are affected by As-related diseases in Bangladesh due to contaminated drinking water. It is therefore very important to check the As concentrations in the air of Bangladesh. The total average As concentration at the five locations in Dhaka was 6.3 ng m<sup>-3</sup>. However, the concentration of As varied from 4.3 ng m<sup>-3</sup> (Medinova

hospital, Dhanmondi) to 7.9 ng m<sup>-3</sup> (Novarties Pharmaceutical, Tejgaon) (Table 4). Unexpectedly high As concentrations (325 ng m<sup>-3</sup>) were observed at all four sites in Bangkok, Thailand (Chuersuwan et al. 2008).

#### Cadmium

Average Cd concentrations ranged from 0.2 to 34.9 ng m<sup>-3</sup>. The lowest value among these five sites was found at Tower Bhaban, Dhaka University campus (residential area), whereas the highest value was observed at Novarties Pharmaceutical, Tejgaon Industrial area. The higher Cd concentration at the industrial site may be due to the release of Cd from different industrial mechanical processes. The total average of Cd in Dhaka (13 ng m<sup>-3</sup>) is slightly higher than that previously reported by Salam et al. 2003, is comparable with those found in Spain (Querol et al. 2002), but if three- to fourfold lower than the values reported for other Southeast Asian sites (Sharma and Patil 1992; Smith et al. 1996).

#### Copper

The average Cu concentrations varied from 31 ng m<sup>-3</sup> (Tower Bhaban, Dhaka University campus) to 132 ng m<sup>-3</sup> (Medinova hospital, Dhanmondi) (Table 4). The average value of Cu was 95 ng m<sup>-3</sup> for PM<sub>2.5</sub>, which is about twofold higher than the value (54 ng m<sup>-3</sup> for TSP) obtained by Salam et al. 2003. The average Cu concentration of five locations in Dhaka, Bangladesh for PM<sub>2.5</sub> was slightly higher than that (65 ng m<sup>-3</sup>) found at four sites in Bangkok, Thailand (Chuersuwan et al. 2008).

#### Iron

The average Fe concentration varied from 225 ng gm<sup>-3</sup> (Jahangirnagar University, Savar) to 669 ng m<sup>-3</sup> (Novarties Pharmaceutical, Tejgaon). The highest value of Fe (669 ng m<sup>-3</sup>) was observed at the Tejgaon industrial area, probably

due to the industrial activities there. The lower value of Fe ( $225 \text{ ng m}^{-3}$ ) at Jahangirnagar University Campus may be due to the lack of industrial activity at this site and also because there is less traffic than at the Novorties Pharmaceutical, Tejgaon site. Iron exhibited relatively higher values at all five sites. The average estimated value of Fe was  $433 \text{ ng m}^{-3}$ . While Fe may originate from soil dusts, poorly managed transport, and building construction, among others, the major sources of Fe are both anthropogenic and crustal in origin, including iron and steel manufacturing units and the weathering of exposed Fe in urban areas. However, the overwhelming source of Fe particles in the atmosphere is from crustal weathering. The average value of Fe was  $433 \text{ ng m}^{-3}$ , which is higher than the concentration found in Los Angeles, USA and Spain (Querol et al. 2002) and also lower than that reported for Asian sites (Fung and Wong 1995; Balachandran et al. 2000).

### Lead

The average Pb concentration varied from  $51 \text{ ng m}^{-3}$  (Jahangirnagar University, Savar) to  $335 \text{ ng m}^{-3}$  (BCIC Bhaban, Motijheel) (Table 4). The higher value of Pb may be due to the presence of heavy traffic at the Motijheel area, while the lower value may be due to relatively lower level of traffic. Lead compounds accumulate with PM in the atmosphere and gradually settle on the Earth's surface. The level of Pb in rural areas in Bangladesh was found to be below the detection limit (Salam et al. 2003). We found the total average concentration of Pb at the five sites in Dhaka to be  $204 \text{ ng m}^{-3}$  of  $\text{PM}_{2.5}$  (Table 4), which is about half the WHO 1999 guideline value of  $500 \text{ ng m}^{-3}$  for urban areas. Scientists at the Bangladesh Atomic Energy Commission (BAEC) observed that Dhaka was the most Pb-polluted city in the world for a part of 1996. A 17-month survey conducted by the scientists of BAEC detected  $463 \text{ ng m}^{-3}$  Pb for  $\text{PM}_{2.5}$  in Dhaka air during the dry months (between November 1994 and January 1996) (Khaliqzaman et al. 1997). However, the atmospheric Pb concentration in Dhaka is decreasing gradually, presumably due to the ban on leaded gasoline in Bangladesh, although it is still higher than that found in European cities (NILU 2002; Manalis et al. 2005) and Far East Asian sites Taiwan ( $133 \text{ ng m}^{-3}$  by Fung and Wong 1995). However, it is lower than that reported for Southeast Asian Sites such as Karachi, Pakistan, and Delhi, Mumbai, and Kanpur, India (Smith et al. 1996; Balachandran et al. 2000; Kumar et al. 2001; Sharma and Maloo 2005).

### Zinc

The average Zn concentrations varied from  $103 \text{ ng m}^{-3}$  (Jahangirnagar University, Savar) to  $516 \text{ ng m}^{-3}$  (Novorties

Pharmaceuticals, Tejgaon) (Table 4). The highest value of Zn at Novorties Pharmaceuticals was probably due to the industrial release of Zn at this location, while the lowest value at Jahangirnagar University campus may be the result of relatively less traffic. The average value of Zn for  $\text{PM}_{2.5}$  was  $381 \text{ ng m}^{-3}$ , which is much lower than the value ( $801 \text{ ng m}^{-3}$ ) obtained at a previous measurement by Salam et al. 2003 for TSP. Elevated concentrations of Zn have also been observed for other Southeast Asian sites (e.g., Lahore, Pakistan; Smith et al. 1996). The Zn concentration at Dhaka was much lower than that at Delhi (Balachandran et al. 2000) and Kanpur (Sharma and Maloo 2005), India, but much higher than that found in Norway (NILU 2002).

### Conclusions

Atmospheric pollution at five locations in greater Dhaka, Bangladesh, was characterized in terms of trace gases, PM, and heavy metals. The average concentration of  $\text{O}_3$  in the greater Dhaka area was lower than the WHO guidelines value (WHO 2005). Elevated concentrations of PM were observed in Dhaka, but these were still lower than those reported for Southeast Asian sites. Particulate mass originates mostly from fine particles (about 88% of  $\text{PM}_{10}$  mass was from  $\text{PM}_{2.5}$ ). The concentrations of Pb, Zn, Cu, Fe, As, and Cd were much lower than the previous measurements in Dhaka city. In particular, the Pb concentration is decreasing due to ban of leaded fuel in Bangladesh.

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