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Air pollution by fine particulate matter in Bangladesh

Bilkis A. Begum [1], Philip K. Hopke [2], Andreas Markwitz [3]

[1] *Atomic Energy Centre, Dhaka (AECD), P.O. Box: 164, Dhaka, Bangladesh*
[2] *Center for Air Resource Engineering & Science, NY, USA*
[3] *Institute of Geological and Nuclear Sciences (IGNS), 30 Gracefield Road, Lower Hutt, NZ, USA*

ABSTRACT

In Dhaka, Bangladesh, particular matter (PM) is the air pollutant that is most harmful to public health and the environment when compared to other measured criteria pollutants. During recent years, the Government of Bangladesh has tried to control PM emissions coming from anthropogenic sources. About 30–50% of the PM_{10} mass in Dhaka (depending on location) is in fine particles with aerodynamic diameter less than 2.2 µm. These particles are mainly of anthropogenic origin and predominately from transport–related sources. However, the combination of meteorological conditions, long–range transport during the winter and local sources results in PM concentrations remaining much higher than the Bangladesh National Ambient Air Quality Standard (BNAAQS). It has been found that black carbon accounted for about 50% of the total fine PM mass before the adoption of control policies. As a result, the PM emission as well as BC has not increased in proportion to the increase in the number of combustion sources like motor vehicles, diesel power generator or brick kiln. Positive Matrix Factorization (PMF) was applied to fine particle composition data from January 2007 to February 2009. It was found that motor vehicles contribute less BC with respect to brick kiln industry. This result demonstrates the effectiveness of the government's policy interventions since previously vehicles represented the major contributors of BC. BC is also transported over long distances, mixing with other particles along the way as demonstrated by a potential source contribution function analysis. Trans-boundary transport of air pollution in the South Asian region has become an issue of increasing importance over the past several decades. The relative amounts of local and long–range transported pollutants are currently unknown.

Keywords: *Particulate matter, black carbon, transboundary transport, Dhaka*

Corresponding Author:
Philip K. Hopke
☎ : *+1-315-268-3861*
🖷 : *+1-315-268-4410*
✉ : *hopkepk@clarkson.edu*

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1. Introduction

The effects of global climate change are now recognized as threats to sustainable development activities. Climate forcers include CO_2 that absorbs infrared radiation and lifetime is decades to centuries with about 20% persisting for millennia (IPCC, 2007), black carbon (BC) that absorbs solar radiation and is a short–lived climate forcer, and methane (CH_4), which absorbs infrared radiation better than CO_2 and produces ozone (O_3), and CO emissions that control the concentration of background tropospheric ozone. Bangladesh is in a vulnerable position with respect to climate effects because of its topographical position. The climatic impacts on Bangladesh will be sea level rise, increased water salinity, drought, increased flooding, and changes in seasonal weather behavior (i.e., some seasons will be extended while others will shorten) (IPCC, 2007; Bollasina et al., 2011).

Climate change and air pollution are linked in many ways. Greenhouse gases (GHG) including CO_2, N_2O, CH_4, and major air pollutants like ozone, CO, and black carbon (BC) particles come from a variety of sources. In developed countries, fossil fuel combustion produces large quantities of CO_2. Sources in the developing countries include biomass burning, brick making, and traffic. Low efficiency combustion of fossil fuels emits black carbon particles and precursor gases that lead to the formation of tropospheric ozone. Black carbon (BC) is a major air pollutant and can act in two ways. First as a direct absorber of visible light and that provides direct warming in the lower atmosphere. The deposition of black carbon on the Himalayan glaciers (Parry et al., 2007; Cao et al., 2010) is a significant contributor to the rapid melting that has been recently observed. The impact of BC concentration on global climate change has not been adequately considered to date, but recent studies have shown it could be the second largest contributor to global warming (Ramanathan and Carmichael, 2008). Black carbon and tropospheric ozone, an element of smog, are not normally concerted to be greenhouse gases, but they warm the air by directly absorbing solar radiation. Compared with CO_2 that can persist in the atmosphere for up to 3 000 years, black carbon remains for only 2 weeks and methane for no more than 15 years.

The visible impact of air pollution is haze, a layer of particles from biomass burning and industrial emissions. This Asian Brown Cloud has a brownish color and this brown cloud phenomenon is a common feature of industrial and rural regions around the world. Because of long–range transport of air pollutants, mostly urban (fossil fuel related) and/or rural (biomass burning and brick kilns) phenomenon is transformed into a regional haze (or cloud) that can span large areas including a substantial part of a continent. It is now becoming clear that the brown cloud may have huge impacts on agriculture, health, climate, and the water budget of the planet (Ramanathan et al., 2005; Ramanathan and Carmichael, 2008). The haze consists of a combination of droplets and solid particles. The liquid droplets in the haze are generally less than 1.0 µm in radius (Pandve, 2008). Begum et al. (2011a) found that BC particles are mainly in the PM_1 range that can contribute to haze formation.

There are two possible sources for the particles in haze. They are either generated naturally (e.g. sea salt, soil dust) or are man-made (e.g., sulfate and soot). From an aerial view, the haze appears brown when the fraction of carbonaceous materials mainly organic or soil dust is large. The potent haze lying over the entire Indian subcontinent from Sri Lanka to Afghanistan has led to weather modifications, sparking floods in Bangladesh, Nepal, and northeastern India but drought in Pakistan and northwestern India (Ramanathan et al., 2007; Bollasina et al., 2011).

The characterization of these fine particles is very important for regulators and researchers because of their potential impact on human health, their ability to travel thousands of kilometers crossing international borders, and their influence on climate forcing and global warming (IPCC, 2007). In order to have an efficient air quality management (AQM) system and its related regulatory approaches, it is important to have reliable air quality data and understand its temporal and spatial distributions.

In Bangladesh, the Atomic Energy Centre, Dhaka (AECD) of Bangladesh Atomic Energy Commission (BAEC) has been monitoring $PM_{2.5}$ and $PM_{2.5–10}$ as part of regional air pollution monitoring network of 15 countries in Southeast Asia and the Pacific under Regional Cooperative Agreement (RCA) with financial assistance from International Atomic Energy Agency (IAEA) (Hopke et al., 2008). The purpose of this project is to improve air quality in the Asian region by applying advanced nuclear analytical techniques (NATs) to the assessment of airborne particulate matter (APM) pollution. The specific objectives of this project are: (1) to obtain sufficient long–term data on fine and coarse APM to identify the anthropogenic and natural pollution sources and to assess the extent of their impact; (2) to obtain sufficiently high–quality data from a sufficient number of Member States within the region covering the same time frame to facilitate a study of larger–scale trans–boundary pollution and transportation sources; (3) to create a reliable high–quality region–wide database that will enable government air–quality managers to make informed decisions on pollution abatement and control strategies, and (4) to assess the climate change effect. Over the years, the BAEC has obtained sufficient PM data to assess the trends and spatial distribution of fine PM.

High fine PM concentrations have been measured in Dhaka and are likely to have substantial public health impacts (Gurjar et al., 2010). Therefore, only fine PM data have been analyzed in this work. This paper reports the trends of air particulate matter in Dhaka based on data obtained from the BAEC monitoring station. The impact of governmental policies on the air quality is assessed using these data. Additionally, the location of fine particle sources ($PM_{2.2}$) and BC concentrations that are major causes of haze in the South Asian region are explored using back–trajectory methods. The main objectives of this paper is to discuss the present status of particulate pollution in Dhaka, Bangladesh, its sources, and the likely locations of the sources of significant events of fine particles ($PM_{2.2}$) and BC concentrations over the region. These sources are major causes of haze in the South Asian Region, especially during the wintertime.

2. Materials and Methods

2.1. Sampling

BAEC sampling site. The Atomic Energy Centre, Dhaka (AECD) of BAEC operates a sampling site (semi–residential) for collecting PM samples using a "Gent" stacked filter sampler (Hopke et al., 1997) capable of collecting air particulate samples in coarse (2.2–10 μm) and fine (2.2 μm,) size fractions together. PM_{10} concentration may be obtained by adding $PM_{2.2}$ and $PM_{10–2.2}$ concentrations.

At the semi–residential area (SR) site, the sampler was placed on the flat roof of AECD campus building. The roof height was 5 m and the intake nozzle of the sampler was located 1.8 m above the roof. The intake was about 80 m away from the roadside. The sampler was placed so that the airflow around it was unobstructed. The airflow of the sampler was maintained at 17 L/m. This site began operation in December 1996. In this paper, the mass and BC concentrations data are presented through December 2011. The location of the sampling station in Dhaka is shown in Figure 1.

Samples were collected only on weekdays. There were generally no samples collected on Thursdays or Fridays. Samples were most commonly collected on Sunday and Wednesday. The samples were collected on Nuclepore filters with 8 μm pores for the coarse fraction samples and 0.4 μm pores for the fine fraction samples. The diameter of the filter is 47 mm. The filters were equilibrated for 24 hours, weighed in an air–conditioned room (approximate temperature of 22 °C and relative humidity of 50%) and stored in airtight petri slides. After sampling, the sample holder (NILU Stacked Filter Unit) was returned to the AECD Laboratory for recovery of the filters and the samples were equilibrated under the same conditions. The post–sampling weighing of the samples was usually completed within one month of the sampling date. A comparison of this sampler with an Airmetrics MiniVol sampler (Baldauf et al., 2001) showed that the Gent sampler provides comparable sampling efficiency (Begum and Biswas, 2005).

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

2.2. PM mass and BC determination

The masses of the coarse and fine fraction samples were determined by weighing the filters before and after the exposure. A Po–210 (alpha emitter) electrostatic charge eliminator (STATICMASTER) was used to eliminate the static charge accumulated on the filters before each weighing.

The concentration of black carbon (BC) in the fine fraction of the samples was determined by reflectance measurement using an EEL–type Smoke Stain Reflectometer. Secondary standards of known black carbon concentrations are used to calibrate the reflectometer (Biswas et al., 2003). Comparisons of the measured elemental carbon (EC) showed good agreement with the BC measurements for similar samples (Salako et al., 2012).

2.3. Multielemental analysis

Multielemental analyses of the samples were made using proton induced X–ray emission (PIXE) at the Institute of Geological and Nuclear Science (IGNS), New Zealand. The X–ray spectra obtained from PIXE measurements were analyzed using the computer code GUPIX (Maxwell et al., 1989; Maxwell et al., 1995). Concentration data for seventeen elements, and black carbon, were used for data analysis of the period of 2007 to 2009. The total number of samples were 166.

2.4. Positive matrix factorization modeling

PMF is a source–receptor model that solves the equation:

$$X_{ij} = \sum_{i=1}^{p} g_{ik} f_{kj} + e_{ij} \tag{1}$$

where x is the matrix of ambient data collected at the receptor site, consisting of the species starting from Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, Cr, Mn, Fe, Cu, Zn, Br, Pb, and BC in columns and dates in rows, g is the matrix of source contributions, where each source k contributes to each sample i, and f is the mass of each element j in each source k (Paatero and Tapper, 1993; Paatero and Tapper, 1994; Paatero, 1997). The best solution was found to be seven factors for elemental compositions of the fine particulate matter fraction in the semi–residential area based on the distributions of the scaled residuals and the interpretability of the resulting source profiles.

PMF2 has the ability to handle the incomplete data such as missing data, below detection limit data and negative values after blank correction by giving low weights to such data points. In this work, any missing data were replaced by the geometric mean of corresponding elements. Half of the detection limit was used for any value below detection limit and its uncertainty (Polissar et al., 1998).

The other important feature for this analysis was using FPEAK to control rotations in PMF2. By setting positive value of FPEAK, the routine is forced to subtract the F factors from each other yielding more physically realistic solutions (Paatero et al., 2002). An additional approach, called G space plotting for PMF modeling (Paatero et al., 2005) was utilized to explore the rotational ambiguity. This idea derives from the concepts of edges representing correlation in the results. The G space plotting helps to identify the edges that show the factors that are "independent" in the factor analysis. The rotation can then be controlled by FPEAK until an appropriate distribution of the edges is achieved.

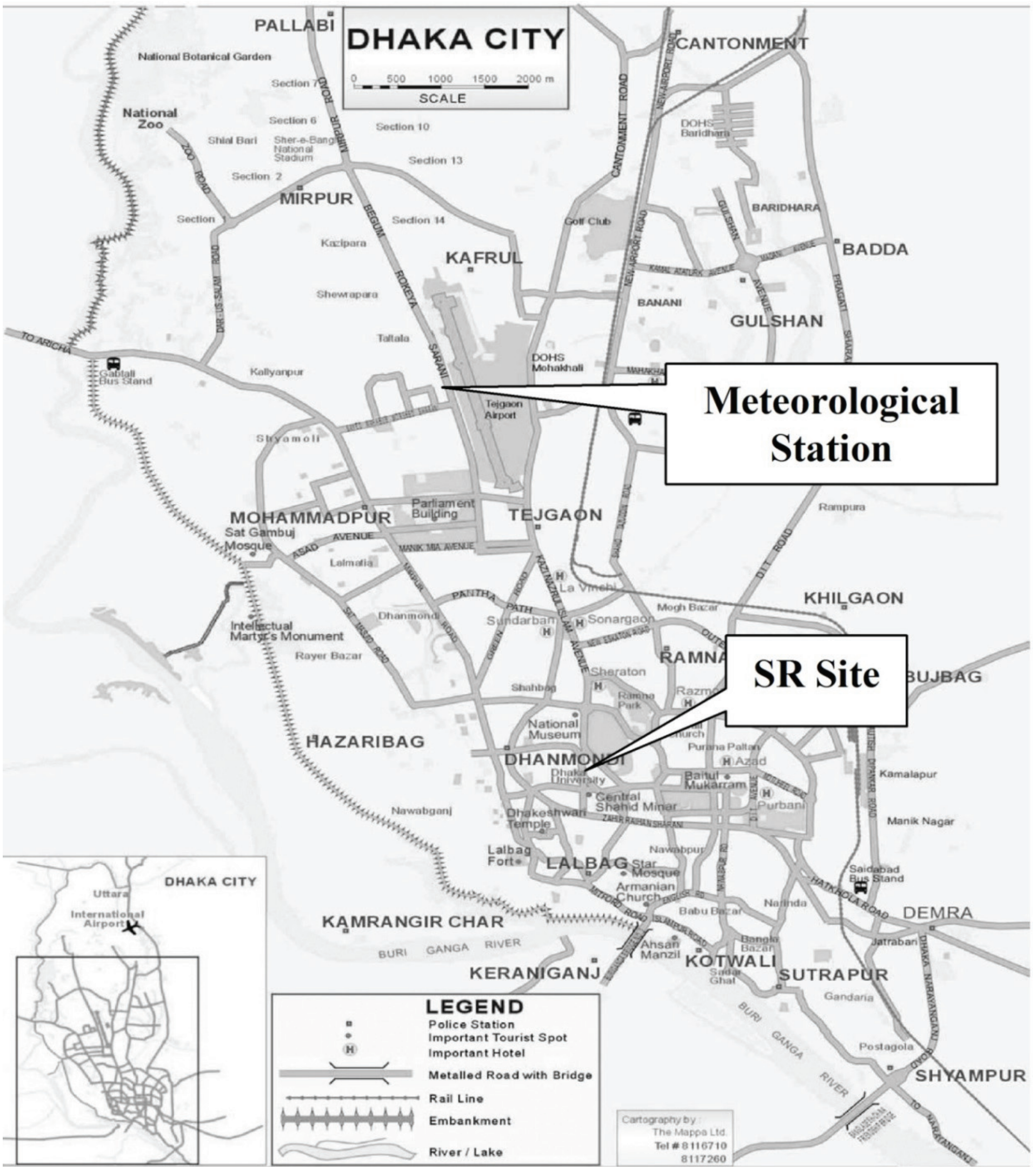

Figure 1. *Map showing the sampling location in Dhaka, Bangladesh.*

2.5. Trajectory model

The NOAA Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT–4) model (Draxler and Rolph, 2003) was used to calculate the air mass backward trajectories for those days when fine particles were sampled at four sites during the periods 2002–2007 (Begum et al., 2011c). The vertically mixed model starting at 500 m above the ground level was used to calculate the five–day backward trajectories arriving every five hours at the receptor site producing approximately 720 endpoints per sample. A starting height of 500 m has been used based on the results of 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; Lee and Hopke, 2006). This height was chosen to diminish the effects of surface friction and to represent winds in the lower boundary layer. Samples were generally collected twice a week. The geophysical region covered by the trajectories was divided into 6 050, 7 776, 5 100, and 2 816 (for Dhaka, Mumbai, Islamabad and Colombo respectively) grid cells of 1°×1° latitude and longitude so that there are approximately 42, 27, 26 and 42 trajectory end points (for Dhaka, Mumbai, Islamabad and Colombo, respectively) per cell on average.

2.6. Potential Source Contribution Function

The error associated with the trajectory segment increases as the distance from the receptor site increases. In a trajectory ensemble approach, the collective properties of a large number of end points are used to estimate a conditional probability field that represents the likely location of PM sources. If the errors in the endpoint locations are randomly distributed, then using a sufficient number of end points distributed over the region of interest should provide a reasonable estimate of the cell–by–cell probability values. Thus, the Potential Source Contribution Function (PSCF) model provides a means to map the source potentials of geographical areas. It does not apportion the contribution of the identified source area to the measured receptor data.

Air parcel backward trajectories were related to the composition of collected material by matching the time of arrival of each trajectory at the receptor site. The movement of an air parcel is described as series of segment end points defined by their latitude and longitude. The backward trajectories were calculated for each sample collected during the period of January 2002 to February 2007. PSCF values for each grid cell were calculated by counting the trajectory segment endpoints that terminate within the grid cells. The number of endpoints that fall in the ij^{th} cell is *n(i, j)*. The number of endpoints for the same cell when the corresponding samples show concentrations higher than an arbitrarily criterion value is defined to be *m(i, j)*. The PSCF value for the ij^{th} cell is defined as:

$$PSCF(i,j) = m(i,j)/n(i,j) \tag{2}$$

In the PSCF analysis, it is likely that the small values of n_{ij} produce high PSCF values with high uncertainties. In order to minimize this problem, an empirical weight function $W(n_{ij})$ proposed by Han et al. (2004) was applied when the number of the end points per a particular cell was less than about three times the average values of the end points per cell. The Equation (3) has been calculated in case of Dhaka, Bangladesh.

$$W(n_{ij}) = \begin{cases} 1.0 & n_{ij} > 84 \\ 0.75 & 42 < n_{ij} \leq 84 \\ 0.5 & 21 < n_{ij} \leq 42 \\ 0.15 & 0 < n_{ij} \leq 21 \end{cases} \tag{3}$$

2.7. Meteorological conditions

In Bangladesh, the climate is characterized by high temperatures, high humidity most of the year, and distinctly marked seasonal variations in precipitation. According to meteorological conditions, the year can be divided into four seasons, pre–monsoon (March–May), monsoon (June–September), post–monsoon (October–November) and winter (December–February) (Salam et al., 2003). The winter season is characterized by dry soil conditions, low relative humidity, scanty 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 prevailing direction changes to southwesterly (marine). During monsoon season, the wind speed further increases and the air mass is purely marine in nature. In the post–monsoon season, the rainfall and relative humidity decreases as does the wind speed. The direction starts shifting back to northeasterly. The meteorological data used in this study was obtained from a local meteorological station, located about 5 kilometers north of the semi–residential (SR) site.

3. Results and Discussion

3.1. Particulate matter mass and black carbon concentrations

Table 1 presents a summary of the $PM_{2.5}$ particulate mass and BC concentrations at Dhaka from December 1996 to December 2011. It can be seen from the Table 1 that the standard deviations of fine mass and BC concentrations are very high because of significant day–to–day variations in the mass concentrations including BC. The variation in emissions and meteorology like wind speed and wind direction drive this variability. The meteorology is responsible for dispersion and dilution of the pollutants in the atmosphere.

The 24–hour average $PM_{2.2}$ mass fractions for the semi–residential site at Dhaka are shown in Figure 2 as yearly box and whisker plots. The box represents 25% to 75% of the distributions of the yearly $PM_{2.5}$ concentration. The horizontal black bar in the box indicates the median and horizontal red bar sign denotes the mean of the distribution for that year. The points lying outside the range defined by the whiskers (extreme events) are plotted as outlier dots.

From the time series plot (Figure 3), it is observed that in winter and early pre–monsoon, the mass concentrations are particularly high. High peak fine mass concentrations are found in December, 2005 to January, 2006. From NASA website (http://earthobservatory.nasa.gov/NaturalHazards), it was found that there was pollution and fog mixed at the base of the Himalayas in India in late December 2005. This haze hangs so thickly over the region that the underlying ground surface is barely visible. In contrast, the air is much clearer over the Himalayas. Heavy air pollution is common in this region between December and February, and it often collects at the base of the mountains. According to news reports, the haze combined to reduce visibility enough to delay air and rail travel on December 23, 2005 (Begum et al., 2011b). No flights could depart from or arrive in Delhi's airport until late morning. Scientists studied that the cloud of haze that frequently lingers over parts of Asia from Pakistan to China and even the Indian and Pacific Oceans has called the pollution the "Asian Brown Cloud". The Asian Brown Cloud is the mixture of aerosols (tiny particles suspended in the air) includes smoke from agricultural and home heating and cooking fires, vehicle exhaust, and industrial emissions. In addition to the respiratory problems the persistent haze can cause, it also appears to hinder crops by blocking sunlight and could be altering regional weather. It has also been found that heavy monsoon rains pelted northern India and Bangladesh between July 5–14, 2008, resulting in floods and landslides that claimed 20 lives. Eleven people died in monsoon flooding and landslides in Nepal in early July, 2008 (NOAA, 2008).

Source apportionment results in the present study show high sea salt concentrations in this day. In winter and pre–monsoon, the mixing heights become lower and the locally emitted particulate matter is trapped near the ground. Additionally, low rainfall during the winter reduces wet deposition and consequently the particulate matter concentrations increase. On the other hand, in winter, northwesterly wind blows over Bangladesh which carries fine PM mass including BC (Ramanathan and Carmichael, 2008; Begum et al., 2010; Begum et al., 2011c).

It is found that $PM_{2.5}$ concentrations are higher than the Bangladesh National Ambient Air Quality Standard (BNAAQS, 2005) that the data for $PM_{2.5}$ and PM_{10} was presented in Table 2. It can be seen that the mean values are much higher than the 2006 USEPA standard as well as the Bangladesh National Ambient Air Quality Standard for $PM_{2.5}$. From the year–by–year average $PM_{2.2}/PM_{10}$ and $BC/PM_{2.2}$ ratios (Figure 4), it has been found that these ratios remain almost constant after 2003. With the increase of the population and economic development, the numbers of vehicles and power consumption have increased substantially.

3.2. Source apportionment by PMF modeling

From the data, PMF modeling resolved 7 sources for the fine fraction PM samples. The identified source profiles and the mass contribution of each source for this fraction are presented in Figures 5 and 6, respectively. The first source includes BC, Na, Si, K, Mn, Fe, and Pb and represents fugitive Pb source. In Dhaka, there are Pb acid battery factories and Pb smelters where Pb–blocks were prepared from rejected batteries. This profile has no seasonal variation and contributes 6.59% of the fine mass. Lead was removed from gasoline in 1999, but there remains a significant background concentration of lead with occasional samples reaching up to 8 μg/m^3.

The second source profile has included high values of EC, Cl, Zn, and Pb and trace amount of K, Ca and Fe and represents a Zn source (Begum et al., 2004). Zn may come from the galvanizing factories and to increase the reflective properties, Pb is added during manufacturing (Krepski, 1985). There are two–stroke motorcycles and motorbikes in use and they would also produce Zn from the combusted lubrication oil. The contribution of this source is mainly during the rainy season and contributes 4.4% of the fine mass.

The third source profile has high BC, Na, and S and trace amount of Mg, Al, Si, Cl, K, Fe and Zn and represents aged sea salt source and has high contributions in the monsoon season. Because of atmospheric acid displacement reactions, the Cl in NaCl is replaced by S. This source contributes about 6.3% of the fine mass.

The fourth source has characteristics of BC, S, K, Pb, and trace amount of crustal elements, and represents brick kiln source and has seasonal variation. The coal that is burnt in kiln contains 4 to 6% sulfur. During kiln operation, waste materials such as plastic or batteries are also burnt from which Cl, Zn, Pb may be emitted. Due to brick production technology, bricks are produced during dry periods mainly starting from November to early March every year. This source contributes 22% of the fine mass.

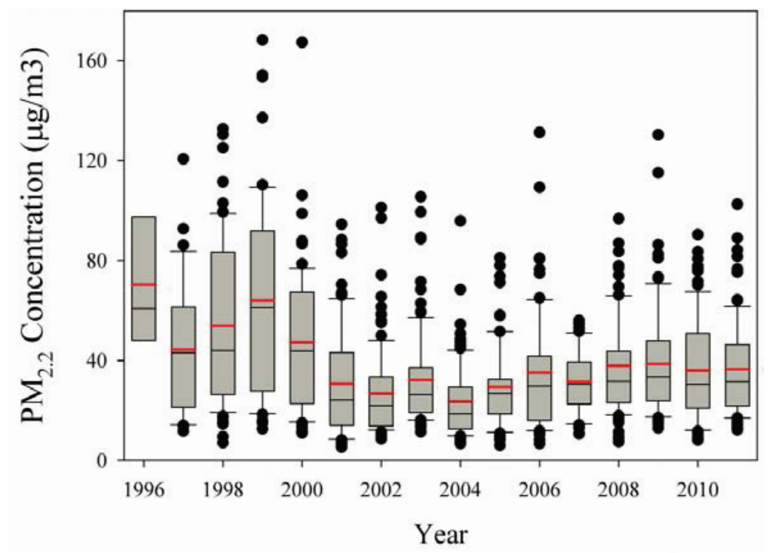

Figure 2. *Box and whisker plots for $PM_{2.2}$ at the SR site.*

Table 1. *Annual summary of PM_{10}, $PM_{2.5}$, BC concentrations, and the ratios of $PM_{2.5}/PM_{10}$ and $BC/PM_{2.5}$ at Dhaka starting from December 1996 to December 2011*

Parameter	Dhaka				
	PM_{10} (μg/m^3)	$PM_{2.5}$ (μg/m^3)	BC (μg/m^3)	$PM_{2.5}/PM_{10}$	$BC/PM_{2.5}$
Mean	97.7	36.7	11.2	0.41	0.32
Median	76.6	29.6	8.37	0.40	0.31
Standard deviation	68.6	25.5	9.48	0.14	0.14
Maximum	491	240	101	0.95	0.96
Minimum	10.1	5.26	1.12	0.10	0.01
Number of filters exposed	1 165				

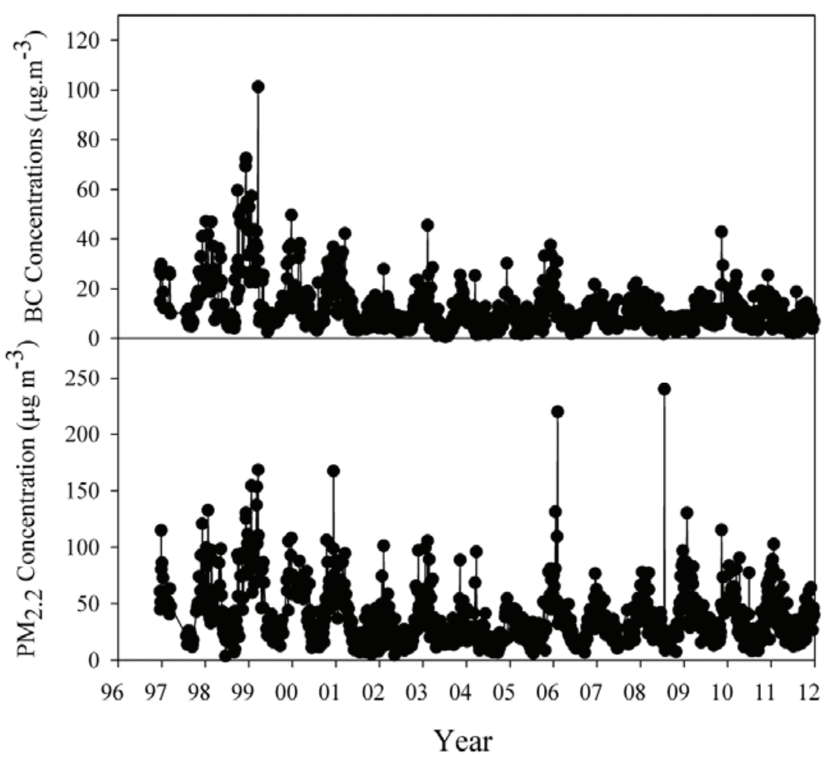

Figure 3. *Time series plots of $PM_{2.2}$ and BC at the SR site.*

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Table 2. *National Ambient Air Quality Standard in Bangladesh (BAAQS, 2005) and comparison with US and WHO*

Pollutant	Averaging time	Bangladesh Standard	US Standard	WHO Standard
$PM_{2.5}$ (µg/m^3)	Annual	15	15	10
	24 hour	65	35	25
PM_{10} (µg/m^3)	Annual	50		20
	24 hour	150	150	50

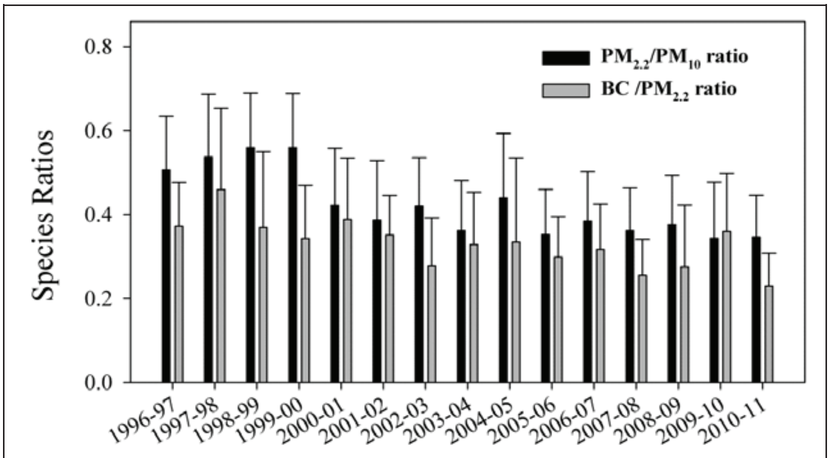

Figure 4. *$PM_{2.2}/PM_{10}$ and $BC/PM_{2.2}$ ratios in different years.*

The fifth source includes BC, Mg, Al, Si, S, Cl, K, Ca, Ti, Fe, and Cu. It represents soil dust and contributes 9.5% of the fine mass. This profile has seasonal variation and has high contribution in winter.

The sixth source is road dust factor and has characteristics of BC, and amounts of Mg, Al, Si, P, S, Cl, K, Ca, Fe and contributes 15% of the fine mass. This source has also seasonal variation and has its highest contribution in winter.

The seventh source has characteristics of BC, and S that is mixed with crustal elements represents motor vehicle source and has a seasonal variation peaking in winter. Traffic in Dhaka is very heavy and most driving is stop–and–go. Diesel fuel in Bangladesh contains about 3 000 ppm sulfur. Heavy duty diesel vehicles mostly use this diesel although they can only be used in Dhaka from 10 pm to 6 am. This source contributes about 36% of the fine particle mass.

The PMF solution was evaluated by comparing the predicted mass of the fine fraction (sum of the contributions from resolved sources) with measured mass concentrations. The sum of predicted BC mass concentrations from all of the sources can be compared with the measured BC mass concentrations. The regression slope and coefficient are slope=0.82, R^2=0.68 and slope=0.99, R^2=0.98 for fine fraction mass and BC concentrations, respectively.

All of the samples used in the present data analysis were collected on weekdays. Table 3 shows the minimum, maximum, average elemental concentrations, standard deviations, and median values of the fine particulate mass (FPM) collected at the semi–residential site (SR) in Dhaka during the period 2007 to 2009. The results of the source apportionment are given in Table 4 and compared with the previous PMF analysis results at the same location for a smaller data set covering the periods of 2001–2002 (Begum et al., 2004) and 2005–2006 (Begum et al., 2011b). The earliest source apportionment results (Begum et al., 2004) showed that vehicles normally produced about 50% of fine particles ($PM_{2.5}$ particles). The most recent source apportionment data (Table 4) shows that the contribution of BC from motor vehicles has decreased following CNG adoption in 2003. It has also found that the highest contribution of BC was from motor vehicles including two stroke engines in 2001 to 2002 (Begum et al., 2004). Air quality policy actions were taken for PM as well as BC emission reductions from motor vehicles. The source apportionment results for the 2005–2006 data showed the reduction of PM as well as BC. However, the results from 2007–2009 data set shows that the contribution of PM emission has increased from the previous years. The emission of BC has been reduced compared to previous years.

Table 3. *Summary fine particulate mass (µg/m^3), EC and elemental concentrations (ng/m^3) used for PMF modeling (2007-2009)*

Parameter	Min	Max	Mean	Std	Median
Mass	7.40	240	37.3	24.6	31.6
EC	1 575	22 417	8 208	4 095	6 941
Na	11.6	3 311	305	308	251
Mg	31.1	2 148	229	209	195
Al	72.8	3 978	482	431	375
Si	132	8 889	1 194	1 023	977
P	14.6	591	124	80.1	107
S	198	15 531	2 476	2 054	1 964
Cl	90.5	2 092	398	341	276
K	113	3 542	644	410	534
Ca	38.3	2 269	347	321	246
Ti	2.99	258	27.5	28.3	21.9
Cr	1.92	45.6	5.01	3.74	4.32
Mn	1.97	219	19.7	26.7	13.4
Fe	32.5	2 653	338	304	259
Cu	1.36	71.5	9.20	7.71	7.45
Zn	44.5	8 078	827	1 071	386
Br	8.92	334	33.1	31.8	22.1
Pb	17.3	1 030	121	137	69.1

The GDP growth in Dhaka has been stagnant, but the growth of motor vehicles continued (Nasrin et al., 2011). As a result the PM emissions from motor vehicles have increased, but the BC emissions have decreased. CNG plays a role in economy of the country. Average CNG usage is 92.19 MMCM per month which is equivalent to 0.065 million liters of petrol/octane. Bangladesh imports about 1.2 million metric tons of crude oil along with 2.6 million metric tons of refined petroleum products per annum. Major consumer of liquid fuel is transport followed by agriculture, industry and commercial purpose. Since the price of CNG is much lower than other fuels, it has been widely adopted. The Government has also decided to ban motorized rickshaws in many parts of Dhaka, without improving public transport, walking, and bicycle riding facilities. As a result, the demand for private cars has increased. The population growth in Dhaka of more than 7% per year with an economic growth of about 6% and vehicular growth of more than 10% (BRTA, 2010). There have also been changes in the nature of the vehicles including the reduction in new two–stroke vehicles, conversion of buses to compressed natural gas, and retirement of old vehicles.

Table 4. *Average source contributions derived from the PMF modeling*

Source	Fine PM samples (µg/m^3) 2001-2002		2005-2006		2007-2009	
	Mass	BC	Mass	BC	Mass	BC
Motor vehicle	7.16	2.50	5.62	0.3	12.1	0.02
Brick kiln	2.23	1.37	11.1	4.1	7.59	7.41
Metal smelters	1.87	0.00	1.94	0.5		
Sea salt	0.19	0.00	0.60	0.0	2.12	0.00
Two Stroke/Zn	1.75	1.11	1.94	1.0	1.49	0.62
Soil dust	1.92	0.0	2.74	0.1	3.21	0.02
Road dust	3.63	1.63	5.14	1.0	4.97	0.57
Fugitive Pb					2.22	0.01
Reconstructed Mass	18.7	6.61	29.1	7.3	33.7	8.12
Measured Mass	22.1	7.90	30.5	9.2	37.3	8.21

However, at the same time, due to the increase of the number of brick production industries, the emission from brick kilns became higher than any other source (Data source 2005–2006) (Begum et al., 2011c). The contribution of BC from the brick kilns is even higher than the motor vehicles based on the data from 2007–2009. Increased activity from the growing economy is a major cause for increased air pollution. Thus, the relatively limited rise in PM concentrations indicates that control actions have helped to balance the increases in pollution that would have been anticipated to parallel the growth in population, economic activity, and vehicles.

The contribution of soil dust including road dust is also higher than the previous years. Therefore, it is necessary to implement a reduction policy for road dust in order to reduce the health risk from PM (Ahmad et al., 2007).

3.3. Transboundary impacts

PM sources. The South Asian Region includes the Indian subcontinent (India, Pakistan, Bangladesh, Nepal and Bhutan) as well as Sri Lanka and Maldives. This region is one of the most densely populated in the world. Three fourths of the region's population live in rural areas, of which about one third are living at the poverty threshold (UNEP and C4, 2002). Deforestation is serious in most of the countries within the region. There are five mega cities with population at or above 10 million in the region: Calcutta, Mumbai, Delhi, Dhaka, and Karachi. These cities are heavily congested and they face vehicular pollution due to diesel/petrol vehicles. Vehicular pollution is a major contributing source especially two–wheel motorcycles/bikes and diesel heavy trucks. The sulfur content in diesel fuel is high (~0.25% to 3.0%) and thus, the direct PM emis-sions are also high. Since 2003, CNG has been used in place of diesel/petrol in Dhaka city. However, heavy–duty diesel trucks, which travel long distance use diesel fuel but they are only allowed on Dhaka streets from 10 pm until 6 am.

India is the only country in the region heavily dependent on coal for energy (307 MT in 97/98 vs. 84 MT of oil and 21.5 MT of natural gas). Bangladesh primarily uses natural gas, Pakistan uses oil and natural gas, and Nepal depends primarily on biomass fuel. Biofuel consumption is also large for India, but the estimates vary widely. Rough estimates are around 150–250 MT of fuel wood, 90–100 MT dungcake, and 40–100 MT agricultural residues. Thus, biofuel could account for about one–half of the total fuel for India. This region is characterized by a tropical monsoon climate with heavy rainfalls. The air pollution problem is insignificant during the rainy season. During this period, the wind mainly comes from the south and southwest. However, when the rainfall becomes minimal, then air quality problems become severe. Both local and regional sources combine to produce unhealthy conditions.

During the winter monsoon, the prevailing low–level winds in the northern Indian Ocean are northeasterly while the prevailing low–level winds in the southern Indian Ocean are southerly. These wind patterns transport continental and anthropogenic aerosols from India and Arabia over large areas of the Arabian Sea and northern Indian Ocean. In order to identify the possible source locations of atmospheric aerosols, particulate matter mass concentrations (Hopke et al., 2008; Begum et al., 2011c) combined with air parcel back trajectories were used to estimate regional source impact. Figure 7 shows the potential areas for PM sources in Pakistan, Bangladesh, India and Sri Lanka. The deep red color shows higher probability locations than the yellow ones. It was found that the air mass travel through Iran, Afghanistan and then reach to Pakistan. In case of Bangladesh and India, the air mass passes along the same route and then curves down to Sri Lanka due to the meteorological condition in this region.

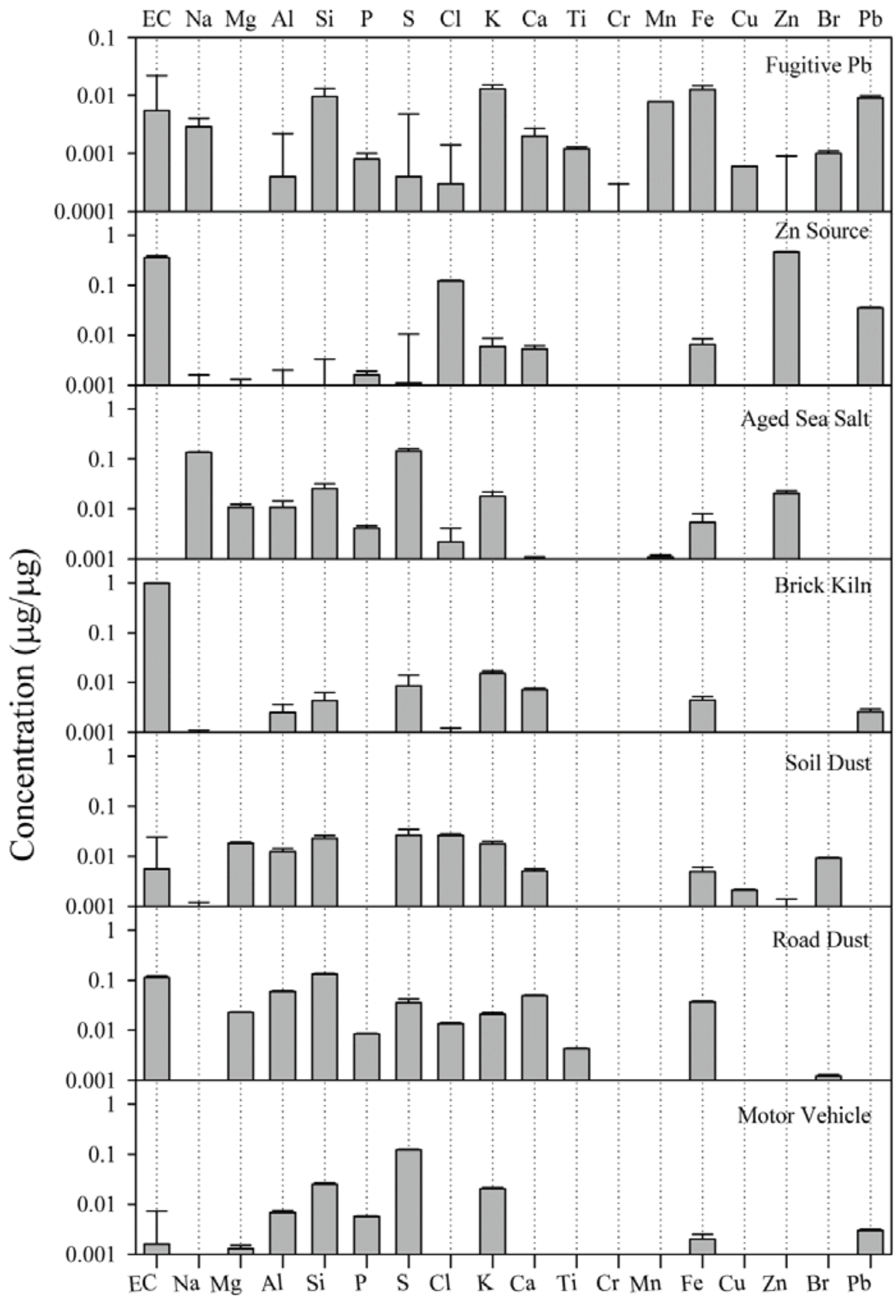

Figure 5. *Source composition profiles for fine particulate matter.*

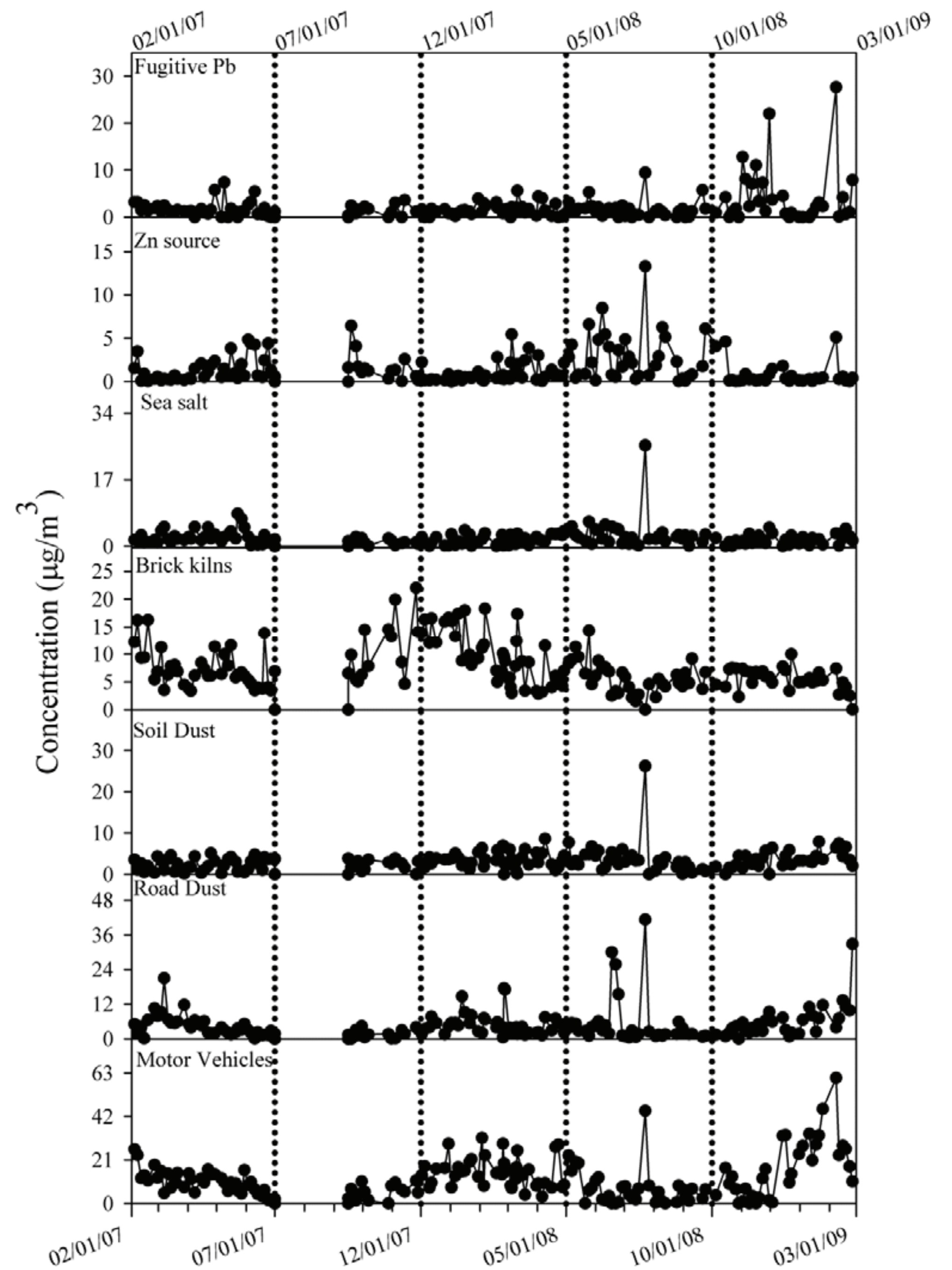

Figure 6. *Time series plots of source contributions for fine particulate matter.*

BC sources. The South Asian region has substantial populations living in rural areas, where domestic energy consumption depends on biofuels such as wood and cow dung, whereas in urban areas soft coke, kerosene, and other liquid fuels are used as well. The economic development of the region is associated with an increasing demand for electricity and the growing use of cars, cause substantial pollutant emissions. About one quarter of the energy use in Asia depends on biofuels. In India this fraction is even larger, close to 50%. Since about half the world's population lives in this region, the potential for high emissions of pollution is large. Thus, biomass burning is also a major source of air pollution in this region.

In order to identify the possible source locations of atmospheric aerosols, BC concentrations were combined with air parcel back trajectories to estimate regional source impact. BC is an important part of the combustion product commonly known as soot. BC in indoor environments is largely due to cooking. On the other hand, outdoor BC comes mainly from fossil fuel combustion (diesel and coal), open burning which is associated with deforestation and crops residue burning. Soot particles can absorb and scatter solar radiation.

Figure 8 shows the potential source areas for BC in Pakistan, Bangladesh, India, and Sri Lanka. The deep red color shows the most potential source areas than the yellow ones. It is found that the air masses travel through Iran, Afghanistan and then to Pakistan. In the case of Bangladesh and India, the air masses come along the same route and then turn down toward Sri Lanka due to the meteorological condition in this region. In the vicinity of the Arabian Sea and Bay of Bengal, there are many ships that also emit BC, S, and other particles.

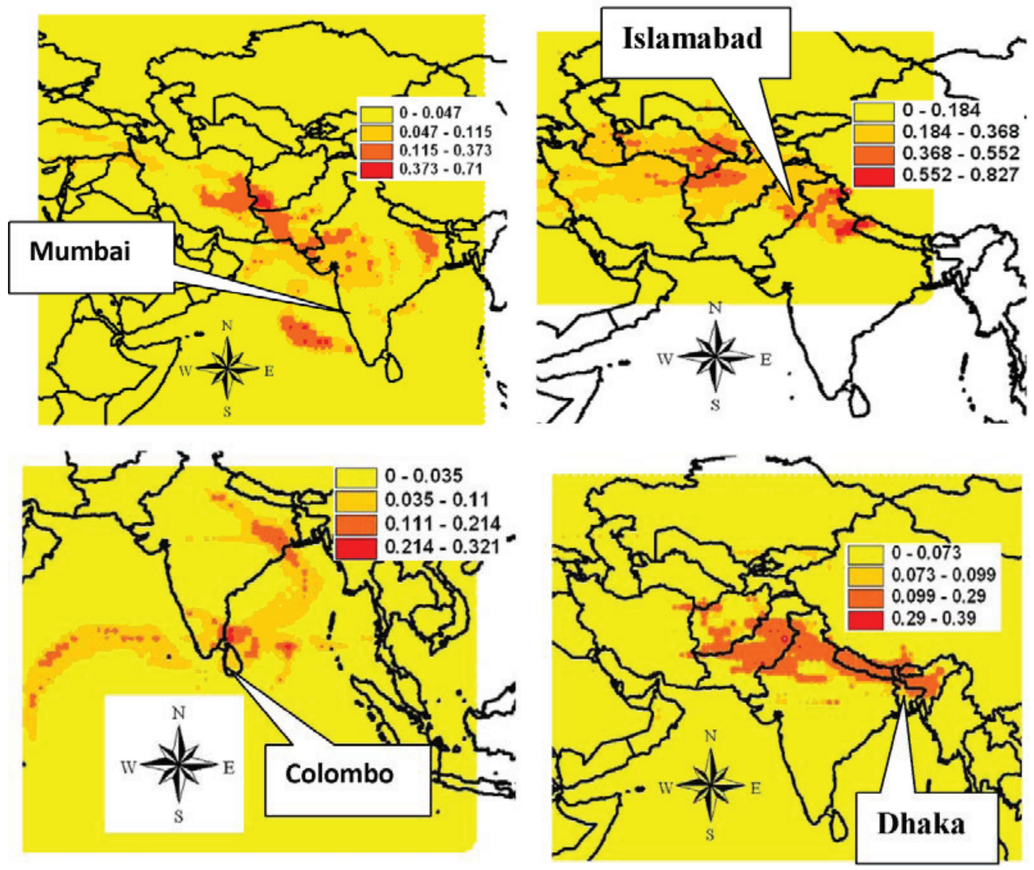

Figure 7. *PM probable source locations across the Indian Subcontinent.*

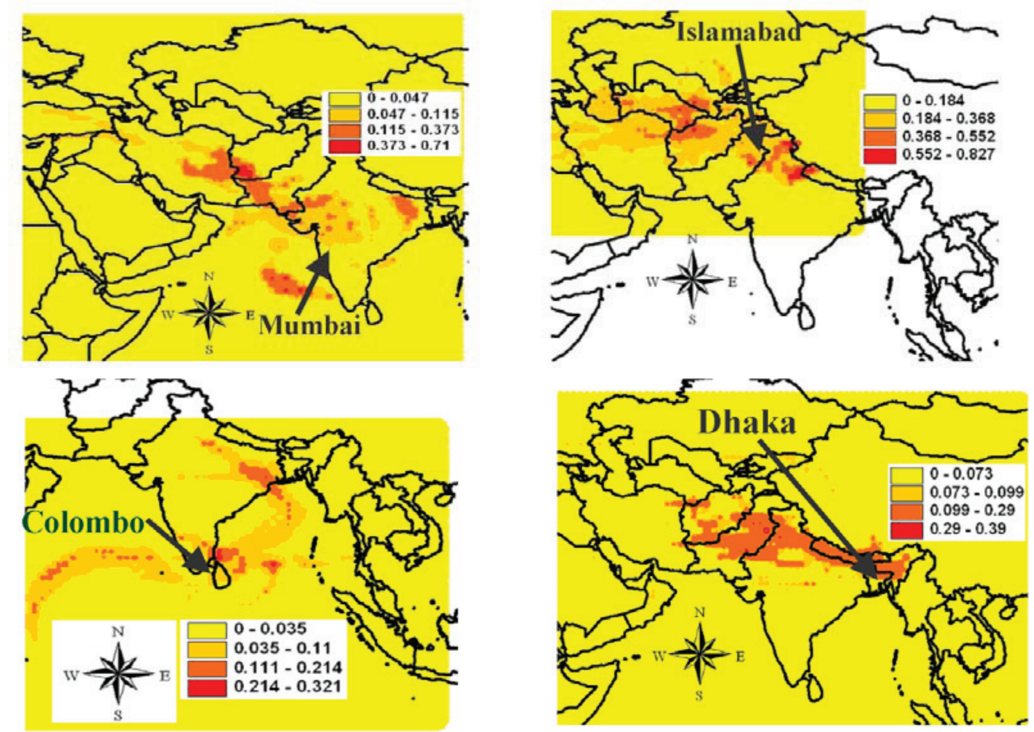

Figure 8. *BC probable source locations across the Indian Subcontinent.*

4. Conclusions

The government of Bangladesh has been working to reduce the PM emissions by introducing lower sulfur fuel, improving the mobility of vehicles, and introducing new technology which is still under consideration for brick production. From this study, it is concluded that there is also trailing effect of PM movement from northwest towards the southeast that affects Bangladesh. This transport happens mainly during the wintertime when rainfall is minimal and wind speeds are low. However, it is not possible yet to quantify the transboundary transport. As a result the local air pollution effect is increased.

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