Atmospheric Research 153 (2015) 526–534

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmos

Characteristics of black carbon concentration at a metropolitan city located near land–ocean boundary in Eastern India

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ARTICLE INFO

Article history:
Received 16 June 2014
Received in revised form 14 October 2014
Accepted 15 October 2014
Available online 22 October 2014

Keywords:
BC concentration
Metropolitan city
Seasonal and diurnal variation
Fossil fuel combustion
Influence of air mass transportation

ABSTRACT

Near surface aerosol black carbon (BC) concentration data were collected using a seven channel Aethalometer (AE31) during June 2012–May 2013 in Kolkata (22° 34′E, 88° 22′N), a metropolitan city located near the land–ocean boundary in Eastern India. BC concentration shows a prominent seasonal and diurnal variation associated with the meteorological parameters. The mean BC concentration varied from 5 μg/m^3 to 27 μg/m^3 seasonally. The variation of BC mass concentration and its significant association with atmospheric parameters such as temperature profile, relative humidity and wind speed have been studied. Moreover, the influence of the transported air masses on BC concentration at different seasons has also been discussed. An estimation of Angstrom exponent discloses that fossil fuel combustion is a major source of BC at this location.

1. Introduction

Among the carbonaceous aerosols, BC is distinctively identified due to its strong absorption over a broad range of visible wavelengths. BC particles significantly influence the regional and global climate (Jacobson, 2001; Dumka and Moorthy, 2010; Ramanathan and Carmichael, 2008; Tiwari et al., 2013). The radiative effect of BC causes enough uncertainties in climate modelling because a significant fraction of net aerosol radiative forcing is caused by BC particles (Andreae et al., 2005; Ramanathan et al., 2007; Kharol et al., 2012; Jacobson, 2001). In recent decades the gradual increase of anthropogenic aerosols such as BC is a matter of great scientific interest because of its impact on climate and environmental quality (Wolf and Hidy, 1997). BC directly causes the heating of the atmosphere by absorbing the short wave solar radiation (Raghavendra Kumar, 2011) and is a major contributor to global warming (Ramanathan and Carmichael, 2008). The existence of considerable quantity of BC in clouds may "burn off" the cloud (Ackerman et al., 2000; Babu et al., 2002). Again, by absorbing solar radiation BC particles reduce the amount of incoming solar radiation and indirectly causes surface cooling (Ramachandran and Rajesh, 2007). BC particles are produced by the incomplete combustion of fossil fuels and biomass in the absence of enough oxygen. Chemically inert BC particles are hydrophobic in nature and are in sub-micron size range (Raghavendra Kumar, 2011). These cause BC particles to have a long atmospheric lifetime so that they are transported to long distances (Moorthy and Babu, 2006; Wolff, 1984; Raghavendra Kumar, 2011). The major sources of BC particles in urban locations are vehicle exhausts, industries, thermal power plant and domestic uses (Kharol et al., 2012). It has been reported that BC emitted by fossil fuel combustion is much more effective in warming of the atmosphere than that from biomass burning (Ramana et al., 2010). Sub-micron size BC particles are breathed in and deposited in the respiratory organs which cause severe health hazards (Raghavendra Kumar, 2011). In view of the significant

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http://dx.doi.org/10.1016/j.atmosres.2014.10.014
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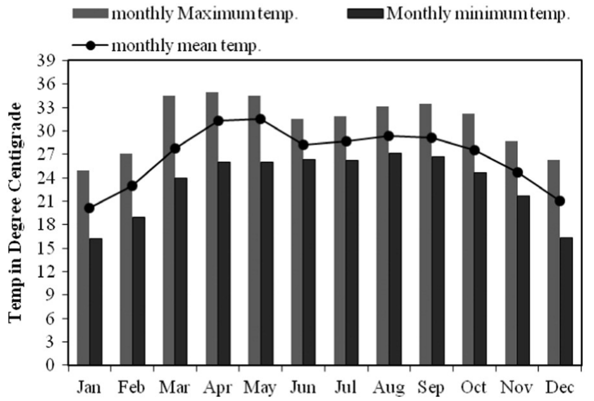

Fig. 1. Annual variation of monthly mean ambient temperature along with monthly mean maximum and minimum temperature values.

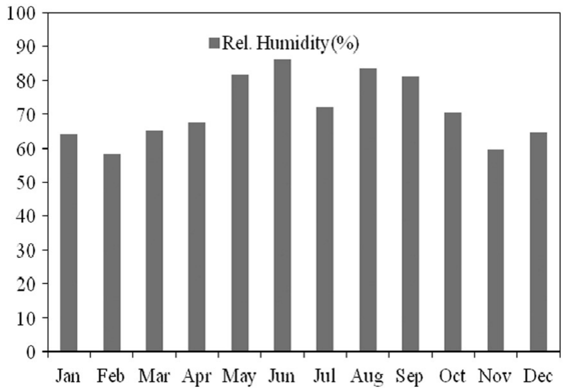

Fig. 2. Annual variation of monthly mean relative humidity.

effect on the atmosphere and human health, it is important to monitor BC concentration at a densely populated location where human activities are mostly responsible for BC production. Kolkata is the third biggest metro city in India after Mumbai and Delhi with a population of more than 14 million in its metropolitan area. Hence, BC and its impact on the environment are matters of serious concern for the location of Kolkata. Moreover, the distinctive presence of pre-monsoon, monsoon and winter seasons in the present location also make it important to study the control of meteorological parameters on the variation of BC content. In the present study, the major source and the behaviour of BC in Kolkata and their association with meteorological parameters are presented, which are hitherto unavailable. The effect of high BC concentration on the ambient heating during post monsoon and winter months has been investigated in this study. The present BC measurement will provide a database to assess the change in the BC concentration pattern in this urban region and resulting environmental consequences in a comprehensive way. The BC concentration in Kolkata has also been compared to that in the other cities of India to obtain a relative scenario.

2. Site description and meteorology

Our measurements have been carried out over Kolkata (22° 34′E, 88° 22′N), a metropolitan city located in Eastern India, on the bank of the river Hooghly. The coastline of the Bay of Bengal is about 110 km from Kolkata towards the south. The city has an average elevation of 6 m above the sea level. Kolkata is one of the most densely populated cities in India. The traffic load is quite heavy in the city and surrounding areas throughout the year. Our observational site is situated in the northern part of Kolkata and our experimental setup is operated at an elevation of 25 m above the ground. During the months of June to September (JJAS), the strong south west summer monsoon is a prevailing feature of this tropical location which is followed by a short span of post-monsoon season from October to November (ON). The winter months are from the December to February (DJF) and the months of March to May (MAM) are considered as the pre-monsoon season when ambient temperature is higher compared to the other seasons. The average ambient air temperature throughout the year is around 26 °C. Fig. 1 shows the mean annual temperature variation along with the monthly average maximum and minimum value. In the pre-monsoon months the monthly mean temperature rises above 32 °C and in the winter it becomes less than 20 °C. In this region, high relative humidity (above 60%) is observed throughout the year and in the monsoon months relative humidity goes above 80% as shown in Fig. 2. Fig. 3(a) shows that the atmospheric pressure is above 1012 mb in the winter months and it remains around 1000 mb during the pre-monsoon and monsoon months. It is evident from Fig. 3(b) that the average wind speed generally remains within 2.5 m/s throughout the year, though in the pre-monsoon months wind speed has higher values.

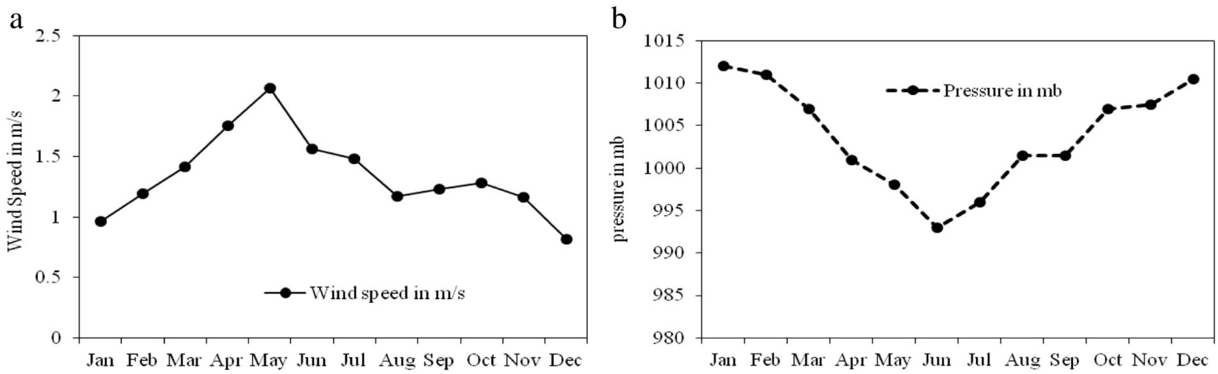

Fig. 3. Annual variation of (a) monthly mean wind speed and (b) monthly mean atmospheric pressure.

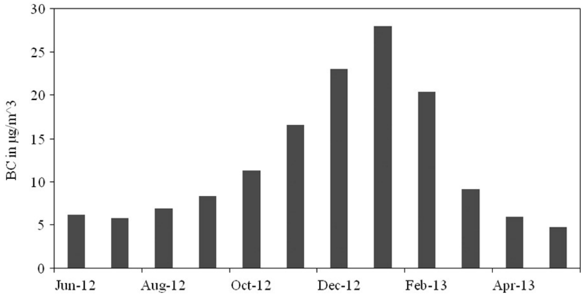

Fig. 4. Annual variations of monthly mean BC concentration.

3. Instrument and database

A seven channel Aethalometer (AE 31) of the Magee Scientific Company, USA was operated in Kolkata to measure the mass concentration of BC particles. Aethalometer samples ambient air through a cyclone inlet at a selected constant flow rate of 4 l/min with 5 min interval. BC particles present in the ambient air are deposited on the quartz filter tape, through which air stream is allowed to pass. BC mass concentration is estimated by measuring the change in transmittance through the filter tape at 880 nm wavelength using the following relation

$$BC = \left(\frac{\Delta ATN}{\sigma}\right) \times A/V \tag{1}$$

where BC is the black carbon mass concentration, ΔATN is the change in attenuation of light through filter tape, σ ($=14{,}625/\lambda$) is the specific attenuation cross section (m^2/g) (Weingartner et al., 2003) and its value is 16.6 m^2/g. A is the spot area of filter tape, and V is the volume of air passed through the filter. The absorption of light transmitted at seven wavelengths viz. 370, 470, 520, 590, 660, 880 and 950 nm is recorded at each cycle of measurement. In practice, the 880 nm is used for standard BC measurement as it is closest to 830 nm at which BC has a maximum absorption and other aerosols have negligible absorption (Bodhaine, 1995).

Uncertainties are involved in the estimation of BC concentration using an Aethalometer as reported in literature (Weingartner et al., 2003; Sheridan et al., 2005; Corrigan et al., 2006). Two calibration factors '*C*' and '*R*' are introduced to Aethalometer attenuation measurement to obtain actual absorption coefficient. The '*C*-factor' comes due to the multiple scattering of transmitted wavelength by the fibres of the quartz filter (Weingartner et al., 2003) and its value is 1.9 as used by Bodhaine (1995). The second factor '*R*' is an empirical correction factor due to the loading of light scattering particles along with BC on the quartz filter and known as 'shadowing effect' which is effective only for pure soot particles and negligible for aged as well as mixtures of aerosol because inclusion of scattering aerosol material reduces the shadowing effect (Weingartner et al., 2003; Arnott et al., 2005). The value of '*R*' is considered to be unity for blank filters.

The Aethalometer is set to function at standard temperature (293 K) and pressure (1013 hPa). At our location ambient temperature is much higher than 293 K and atmospheric pressure is less than 1013 hPa for most of the months of the year. Thus the measured values of BC concentration are corrected for each month using an equation given by Moorthy et al. (2004) as follows

$$M_{BC} = M_{bc}\left[\frac{P_0 T_1}{P_1 T_0}\right]^{-1} \tag{2}$$

where M_{BC} is the actual and M_{bc} is the measured value of BC concentration, P_0 and T_0 are the standard atmospheric pressure and temperature and P_1 and T_1 are the ambient pressure and temperature. For the present location, the actual values of BC concentration in different seasons are 1 to 5% less than the measured value of BC concentration.

Daily ambient temperature, pressure, wind speed and relative humidity data have been obtained using an Automatic Weather Station (AWS) at our location. AWS has different digital sensors to measure the mentioned meteorological parameters.

We obtain the temperature profile data using a multi-frequency microwave radiometer (RPG-HATPRO) operating at

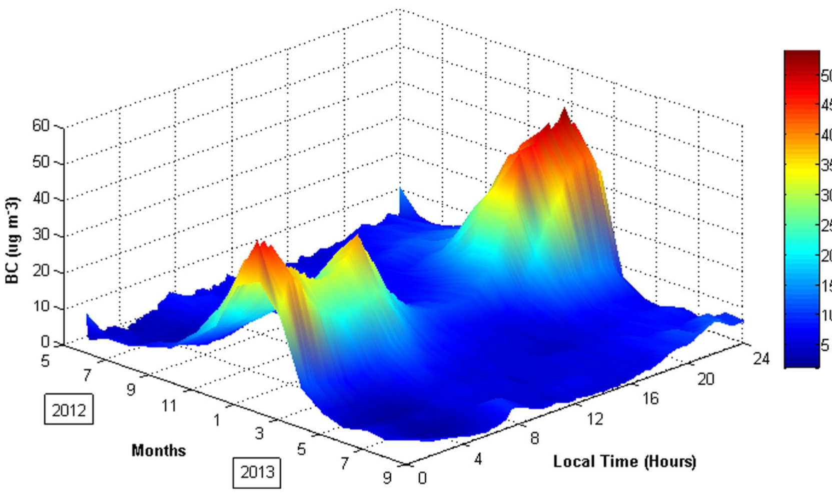

Fig. 5. Annual change of the mean diurnal variation of BC concentration.

Table 1
Average BC mass concentration observed at different urban locations in India. Data are taken from Safai et al. (2007) and Dumka and Moorthy (2010). References are cited therein.

Location (category)	BC (μg m^{-3})	References
Bangalore (urban)	4.2	Babu et al. (2002)
Mumbai (urban and industrial)	12.5	Venkatraman et al. (2002)
Hyderabad (urban)	0.5–68 (dry season), 0.5–45 (wet season)	Latha and Badarinath (2003)
Kanpur (urban and industrial)	6–20	Tripathi et al. (2005)
Delhi (urban and industrial)	29 (±14)	Ganguly et al. (2006)
Agra (urban)	20.6 (7.1–48.3)	Safai et al. (2007)
Ahmedabad (urban and industrial)	3.43 (dry season), 1.3 (wet season)	Ramachandran and Rajesh (2007)
Pune (urban)	4.1	Safai et al. (2007)
Bhubaneswar (urban)	5.2 (dry season)	Das (2010)
Darjeeling	5.6 (dry season)	Chatterjee et al. (2010)
Dibrugarh	11 (dry season)	Gayatry et al. (2010)
Allahabad (urban)	25.4 (dry season)	Badarinath et al. (2007)
Udaipur	5.6	Vyas (2010)
Dehradun (urban)	4.4 (dry season)	Kant and Dadhwal (2010)
Varanasi	14.5	Upadhyay and Singh (2010)
Goa (urban)	2.5	Leon et al. (2001)
Trivandrum (urban)	5 (wet season)	Babu and Moorthy (2002)
Shillong	5 (dry season)	Kundu and Borgohain (2010)
Kullu	4.6	Kuniyal (2010)

our site. It consists of two receiving sections along with a noise diode, a data acquisition system, rain sensor, GPS clock, and a ground pressure and temperature sensor (Rose and Czekala, 2009). RPG-HATRO measures the brightness temperatures at 14 frequencies in two frequency bands (7 frequencies in each band) with an accuracy of 0.5 K. The frequency band of 22–31.4 GHz is used for humidity profiling whereas the 51.26–58 GHz frequency band is utilized to obtain the temperature profile within the troposphere.

4. Results and discussions

4.1. Annual variation of BC mass concentration

The mass concentration of BC exhibits a significant annual variation. Fig. 4 shows that in January, the highest value of BC concentration is observed with a monthly average of 27 μg/m^3 and in the month of May the value is minimum with a monthly average of 5 μg/m^3. Fig. 5 shows the annual change in monthly mean diurnal variation of BC concentration. At our present location, BC concentration obtained during the evening hours of the month of January shows the value around 50 μg/m^3 which is significantly high. The average BC value over Kolkata is quite high compared to many that of other urban or industrial locations in India such as Bangalore (Babu et al., 2002), Hyderabad (Latha and Badarinath, 2003), Kanpur (Tripathi et al., 2005), Pune (Safai et al., 2007), Bhubaneswar (Das, 2010), Darjeeling (Chatterjee et al., 2010), Dibrugarh (Gayatry et al., 2010), Udaipur (Vyas, 2010), Dehradun (Kant and Dadhwal, 2010), Goa (Leon et al., 2001), Trivandrum (Babu and Moorthy, 2002), Shillong (Kundu and Borgohain, 2010), and Kullu (Kuniyal, 2010). It may be noted that all the mentioned cities are less populated than Kolkata. However, BC concentration at Kolkata is comparable with reported BC values at Mumbai (Venkatraman et al., 2002), Allahabad (Badarinath et al., 2007), Varanasi (Upadhyay and Singh, 2010), Delhi (Ganguly et al., 2006), and Agra (Safai et al., 2007). Kolkata has been found to be among the top five BC producing cities in India. The average BC concentrations that are observed at different urban locations in India are shown in Table 1. (Safai et al., 2007; Dumka and Moorthy, 2010). From the month of October BC concentration starts to increase gradually and shows its maximum concentra-

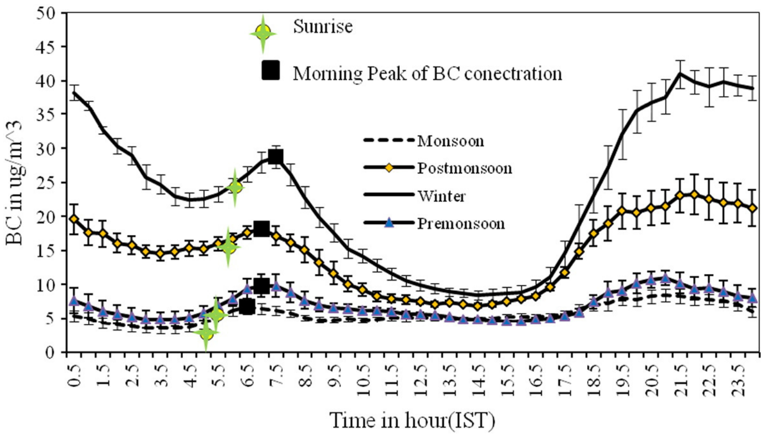

Fig. 6. Seasonal change of the mean diurnal variation of BC concentration.

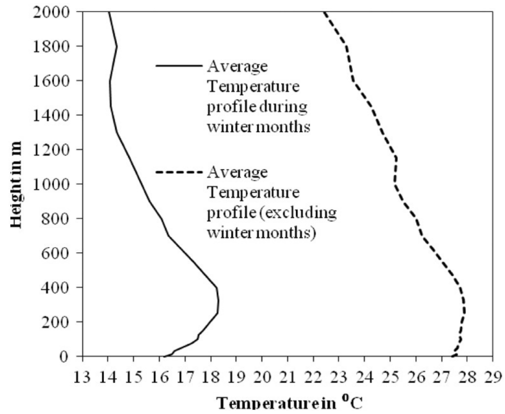

Fig. 7. Comparison of winter season average temperature profile with yearly average temperature profile (excluding winter months).

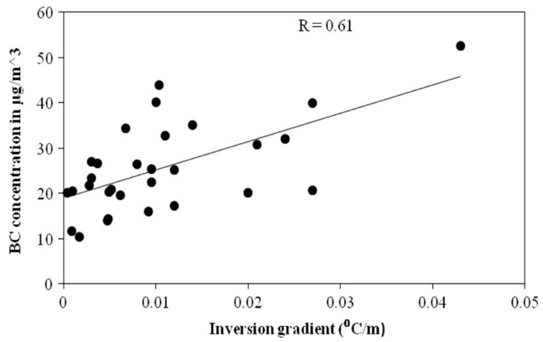

Fig. 8. Variation of BC concentration with respect to gradient of inversion.

tion in January. From the month of February the BC concentration again starts to decrease and in monsoon months it goes down as BC particles are removed from the atmosphere by rainfall.

4.2. Diurnal and seasonal variation of BC mass concentration

Both the mean diurnal and mean seasonal variations of BC concentration are significantly controlled by the atmospheric boundary layer (Moorthy et al., 2004; Nair et al., 2007; Dumka and Moorthy, 2010). Fig. 6 shows that the diurnal variation consists of prominent morning and evening peaks. During the pre-monsoon and monsoon months the morning peak is observed around 06:30 h and the evening peak is around 21:00 h whereas in the winter the morning peak is around 07:30 h and the evening peak is around 21:30 h. Depending on the sunrise time, the timing of the morning peak varies seasonally. The evening peak is associated with the shallowness of the nocturnal boundary layer (Kunhikrishnan et al., 1993; Raghavendra Kumar, 2011) and the morning peak is related to the loading of BC aerosols by local anthropogenic activities and the fumigation effect within the atmospheric boundary layer just after the sunrise (Stull, 1989). It is also evident from Fig. 6 that the morning and evening peak values are much higher in the winter than the rest of the seasons, whereas the noon time minimum values do not have much variation throughout the year due to the extended and well mixed boundary layer at noon and early afternoon hours. In the winter, the average morning peak value is about 30 μg/m^3 and the average evening peak value is about 45 μg/m^3 whereas in the monsoon months, these values are 8 μg/m^3 and 10 μg/m^3, respectively. During the winter season, (December to February) increasing shallowness of the surface layer and the presence of a steady temperature inversion within the lower surface level of atmospheric boundary layer, as shown in Fig. 7, cause the growth of BC concentration by trapping BC particles near the surface (Sreekanth et al., 2007).

4.3. Association of meteorological parameters with BC concentration

The variation of BC mass concentration is significantly influenced by atmospheric parameters, such as diurnal and seasonal features of ambient temperature profile within boundary layer, wind speed, relative humidity and rainfall amount. It may, however, be noted that not only the height of inversion but also the temperature difference between height of inversion and surface level, play an important role to increase BC concentration. Considering this fact a scatter plot between BC concentration and inversion gradient (°C/m) has been made, as shown in Fig. 8. It indicates that the inversion which is simultaneously stronger and nearer to the ground will have more effect on BC concentration. Fig. 9(a) and (b) shows the monthly mean values of wind speed and relative humidity that are negatively correlated with the BC mass concentration with correlation

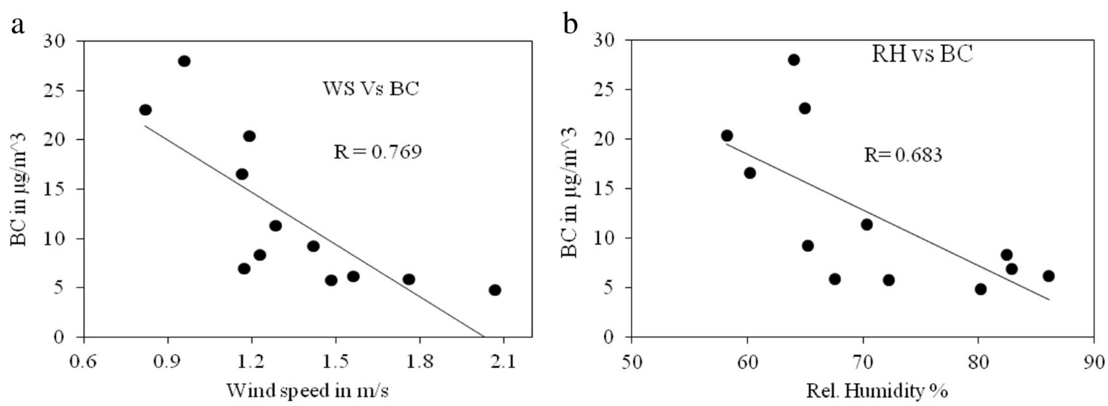

Fig. 9. Correlations of BC concentration with monthly mean (a) wind speed and (b) rel. humidity.

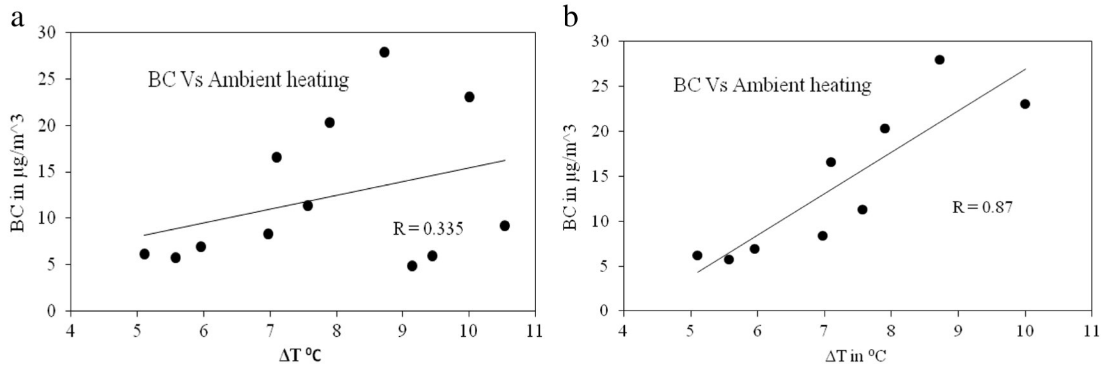

Fig. 10. Influence of BC concentration on monthly mean diurnal temperature change (a) including all the months and (b) excluding pre-monsoon months.

coefficients of 0.76 and 0.68, respectively. It is observed that BC concentration is negatively linked with rainfall and goes down during monsoon. It is known that BC particles influence the ambient heating of the atmosphere (Babu and Moorthy, 2002; Ramachandran and Rajesh, 2007; Dumka and Moorthy, 2010). The correlation between BC concentrations and ambient heating has been studied at the present location. Ambient heating is estimated from the difference between daily maximum and minimum temperatures (Dumka and Moorthy, 2010). A positive correlation (R ~0.34) between BC concentration and diurnal temperature change is observed which is shown in Fig. 10(a). Fig. 10(b) shows that the correlation is actually much stronger (R ~0.87) when pre-monsoon months are not taken into account. In premonsoon season, the expansion of atmospheric boundary layer and increased vertical mixing cause the BC concentration near the surface to decrease. Moreover, distinctly high wind speeds during premonsoon months also notably cause low BC concentration. This causes less control of BC on ambient heating. However, the length of daytime in this season is longest and the daily maximum temperature is highest compared to the other seasons. This causes a significant difference between daily maximum and minimum temperature irrespective of BC concentration, resulting in the degradation of the correlation between ambient heating and BC concentration in the pre-monsoon months. On the other hand, it is observed that the values of ambient heating decrease in the monsoon months when BC concentration is also much lower, providing suitable conditions to have a better correlation between them in this season. Additionally, it may be mentioned that relatively much higher concentration of BC in post-monsoon and winter season significantly increases ambient heating.

4.4. Annual variation of daytime to nighttime ratios of BC concentration

The significant annual variation of the ratios of daytime to nighttime of BC concentration has been studied. It is shown in Fig. 11 that for the winter months (Jan–Feb) the ratio of daytime (6:00–18:00 h) to nighttime (18:00–6:00 h) mean BC concentration is around 0.5. For the months of April to July daytime values are almost comparable to nighttime values and thus the ratio is near about 1. For the rest of the months of the year the daytime to nighttime ratio values are between 0.5 and 1 as nighttime values are higher than daytime values of BC concentration at the present location. This feature of annual variation of daytime to nighttime ratios of BC concentration is opposite to that observed in hilly regions which is related to the atmospheric boundary layer (ABL) dynamics. In hilly regions, aerosols are trapped below the peak of mountain during the daytime. In the afternoon, the suspended particles are forced to go up due to the up-valley wind and BC concentration decreases near the surface. This leads to high BC concentration in daytime than the night for most of the time of the year in the hilly region,

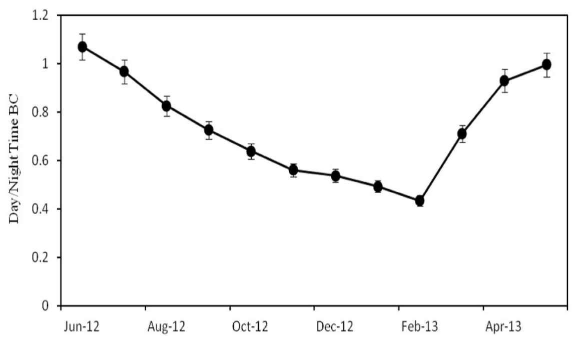

Fig. 11. Monthly variations of daytime to nighttime ratios of BC mass concentration.

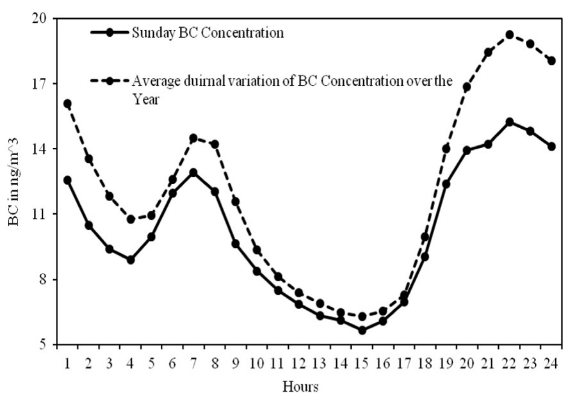

Fig. 12. Difference between the average BC concentrations on working days and Sundays.

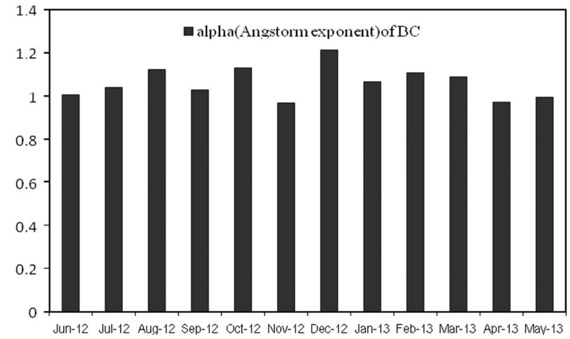

Fig. 13. Variation of monthly mean values of Angstrom exponent (α).

except during the months of June to August (Dumka and Moorthy, 2010).

4.5. Weekend BC mass concentration

On Sundays, the mean BC concentration always shows lower values compared to the weekdays as depicted in Fig. 12. In this region, the mean BC concentration on Sundays decreases by 4% to 22% of the yearly average values. In case of metropolitans like Kolkata, significantly less number of vehicles run on the road on Sundays compared to the weekdays which may be the major cause of lesser BC production on Sundays. This also supports the fact that carbonaceous aerosols emitted during vehicular combustion are a significant fraction of pollution in urban locations like the present one (Chen et al., 2001; Andreae et al., 2005; Ramanathan et al., 2007; Kharol et al., 2012).

4.6. Determination of Angstrom exponent and source identification of BC

The BC absorption coefficient values have been calculated by the following relation (Bodhaine, 1995; Weingartner et al., 2003)

$$\sigma_{abs}(\lambda) = -\left[\frac{(A \cdot \Delta ATN)}{(V \cdot \Delta t)}\right] / \frac{1}{C \cdot R} \tag{3}$$

where ΔATN is the change in attenuation during sampling interval of time (Δt) and is calculated from the relationship $\Delta ATN = -\ln\ (I2\ /\ I1)$, where I_1 and I_2 are the ratios of the intensities of incoming light to the remaining light after passing through an optical path, for sensing beam and the reference beam respectively. In the present case $\Delta t = 5$ min, $V = 4$ l/min,

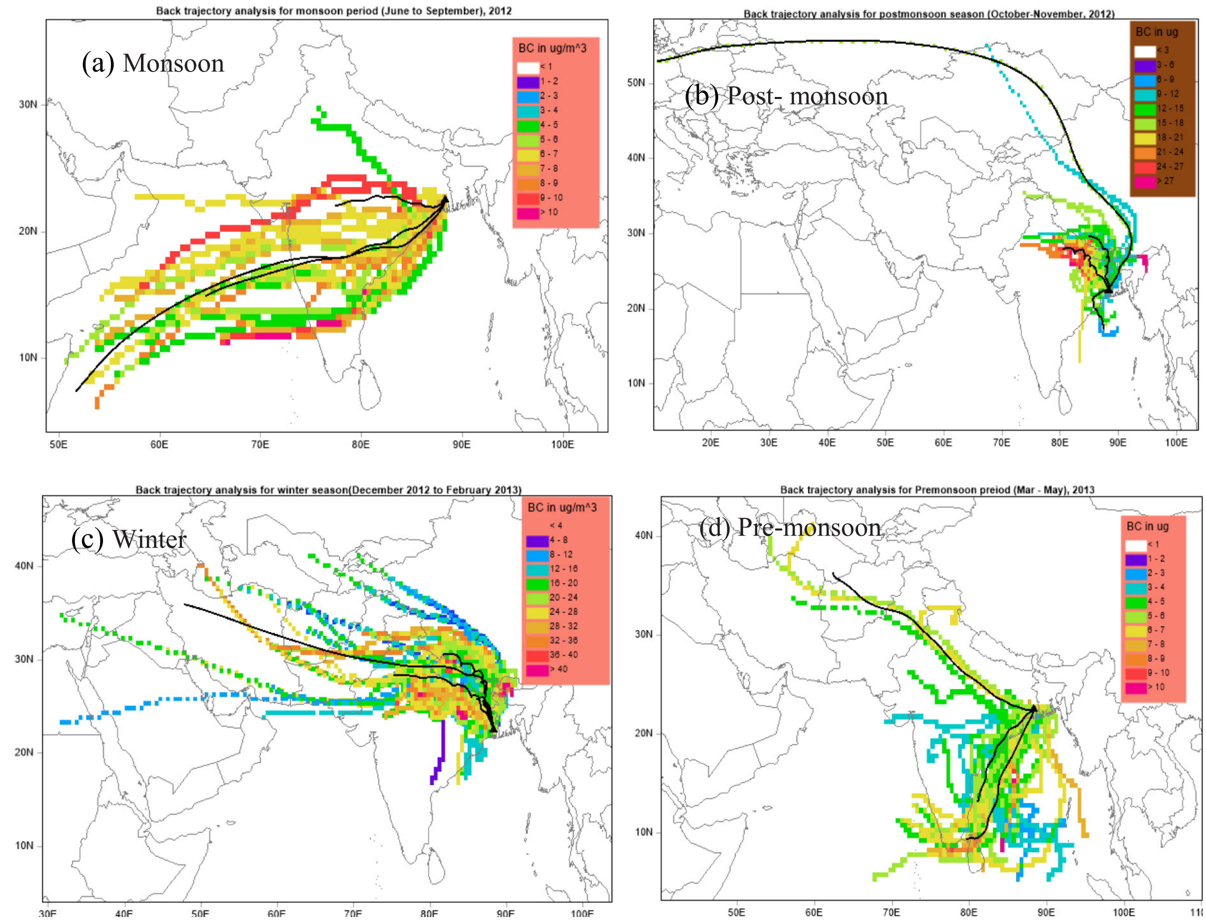

Fig. 14. 7-days back trajectory analysis of BC concentration for (a) monsoon (b) post-monsoon (c) winter and (d) pre-monsoon over Kolkata (arriving at 1000 m agl).

$C = 1.9$ (Bodhaine, 1995), $R = 1$ (Dumka and Moorthy, 2010), and $A = 1.67\ cm^2$ (mentioned by the manufacturer).

The Angstrom exponent (α) is obtained, using calculated values of σ_{abs} to the following relation

$$\sigma_{abs}(\lambda) = \beta\lambda^{\alpha} \tag{4}$$

and performing linear regression of $\ln(\sigma_{abs})$ and $\ln(\lambda)$. Here β is the particle loading and λ is the wavelength.

From the value of α, the probable major source of BC can be identified. It is reported that the BC produced from fossil fuel gives α values close to 1. For biomass burning sources, the value of α is around 1.8 and $\alpha > 2$ represents BC mixed with dust (Kirchstetter et al., 2004). Fig. 13 shows that α values for the present location are close to unity throughout the year, which indicates that BC resulted from fossil fuel burning that dominates over the present location.

4.7. Back trajectory analysis

The 7-day back trajectory analysis of BC concentration during monsoon and winter seasons over Kolkata has been presented using TrajStat, a GIS based software. Meteorological data are collected from the NOAA database (ftp://arlftp.arlhq.noaa.gov/pub/archives/reanalysis/). Fig. 14 shows the long range transport of BC from neighbouring region to the present location arriving at 1000 m above the ground level for different seasons. Fig. 14(a), (b), (c) and (d) shows the back trajectories for monsoon, post-monsoon, winter and pre-monsoon seasons, respectively. It is evident from Fig. 14 that the trajectories from continent are dominant during winter among all the seasons. The continental air mass during the winter can carry BC particles adding to locally generated BC.

5. Conclusions

BC concentration in Kolkata is found to have some distinctive features with significant high values which will have profound effects on climate and human health. Diurnal and seasonal variations of BC concentration show prominent association with meteorological parameters. The mass concentration of BC is significantly influenced by the temperature inversion near the ground. BC shows positive correlation with ambient heating whereas wind speed and relative humidity are negatively correlated with BC mass concentration. The prominent annual variation of the boundary layer dynamics is responsible for the variation of the daytime to nighttime ratios of the mean BC concentration. A major fraction of the total amount of BC concentration results from fossil fuel burning in the region. A fewer number of vehicles running on Sundays than on the weekdays has a significant effect in lessening BC concentration on Sundays. Back trajectory analysis shows that the trajectories from continent during winter might have contributed to the high values of BC concentration in this season.

Acknowledgments

This work has been supported by the grants from the Indian Space Research Organization under the Project "Studies on Aerosol Environment at Kolkata Located Near the Land-Ocean Boundary as a Part of ARFI Network under ISRO-GBP" (SPL:GBP: ARFI:37) being carried out at S.K. Mitra Centre for Research in Space Environment, University of Calcutta.

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