# Seasonal Characteristics of Aerosol Black Carbon in Relation to Long Range Transport over Tripura in Northeast India

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## ABSTRACT

This study presents the characteristics of aerosol black carbon (BC) from a rural continental site, Agartala, located in the North-Eastern part of India using two year measurements from September 2010 to September 2012. Diurnal and seasonal variations are examined in relation to the unique geographical location, changeable meteorological conditions and distinct source characteristics. Winter season is characterized by extremely high BC concentration ($17.8 \pm 9.2$ µg/m$^3$) comparable to those seen in urban environments of India, dropping off to much lower values during the monsoon ($2.8 \pm 1.7$ µg/m$^3$). Even this lowest seasonal mean is rather high, given the rural nature of Tripura. Examination of the spectral dependence of aerosol absorption coefficients indicates that the main source of aerosol to total BC burden at Agartala is the fossil fuel combustions. Concentration weighted trajectory (CWT) analysis indicate that the characteristic high BC during winter is mostly associated with the advection from the Indo-Gangetic Plains (IGP), while the air mass pattern is constricted to the oceanic region during monsoon making BC aloft due to local pollution only.

*Keywords*: Black Carbon (BC); Absorption coefficients; Aerosol transport; CWT analysis.

## INTRODUCTION

The sustained increase in the amount of aerosols due to the large anthropogenic activities is believed to cause irreversible changes in the Earth's regional climate (Babu *et al.*, 2013). Broadly, the aerosols affect the energy budget of the Earth-atmosphere system directly by scattering and absorbing the incoming solar and outgoing terrestrial radiations leading to atmospheric warming and a surface cooling (Charlson *et al.*, 1992; Haywood *et al.*, 1999) and indirectly by modifying and altering the microphysical and optical properties of cloud such as cloud albedo, lifetime of clouds, and drop size distribution (Twomey, 1977; Boucher *et al.*, 1998; Heymsfield and McFarquhar, 2001; Satheesh and Moorthy, 2005).

In the above context, the Black Carbon (BC) is the major anthropogenic and light-absorbing component of atmospheric aerosol system and has got a special significance as it is considered as one of the important contributors to current global warming (Ramanathan and Carmichael, 2008). Black carbon (BC) is the by-product of incomplete combustion of carbonaceous fuel (of fossil fuels, biomass and agricultural wastes and forest fires). The most refractory and light-absorbing component of carbonaceous combustion particles are synonymously referred as "black carbon", "soot", "elemental carbon", "equivalent black carbon" and "refractory black carbon", but the underlying definitions and measurement methods are different (Petzold *et al.*, 2013; Lack *et al.*, 2014). In the present study, we have used optical technique for the measurement of Black Carbon (BC). According to Patzold *et al.* (2013), all light-absorbing carbonaceous substances in atmospheric aerosol can qualitatively described as Black carbon (BC). But, when mass concentration of BC is derived from optical absorption methods together with a suitable MAC (mass-specific absorption cross section) for the conversion of light absorption coefficient into mass concentration, then Equivalent black carbon (EBC) should be used instead of BC. In the present study the term EBC represents 'Equivalent BC'

Being mostly in the sub-micron range and chemically inert, EBC has a long atmospheric lifetime from several days to weeks depending on the meteorological conditions and hence is susceptible for long-range transport (Reddy and Venkataraman, 1999; Babu and Moorthy, 2002). BC induces direct radiative forcing by reducing directly the incoming short-wave solar radiation at the Earth's surface mainly

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through absorption, leading to heating of the atmosphere (Horvath 1993; Jacobson, 2001; Babu *et al.*, 2002). If significant quantities of EBC is present in the lower and mid-troposphere, it could strongly modify the vertical temperature structure (Babu *et al.*, 2011) and affect the cloud microphysical properties and thereby rainfall mechanisms (Satheesh and Ramanathan, 2000; Menon *et al.*, 2002). Due to its potential to alter the radiation budget and its climatic significances, BC aerosol and its characterization have got a great interest in recent times (Haywood and Ramaswamy, 1998; Hansen *et al.*, 2000; Jacobson, 2001).

The Indo-Gangetic Plains (IGP, Fig. 1, shown within the black line boundary) encompasses a densely populated, (accommodating ~40% of the Indian population) vast area (accounting for ~21% of the land area of India). Using trajectory clustering and concentration weighted trajectory analysis; Gogoi *et al.* (2011) have shown that IGP are the potential source regions, which contribute to total aerosol abundance over North East India. The IGP region is always a hotspot of interest for the aerosol researchers as the region, apart from being a major source region for aerosols, is bordered by densely industrialized areas on the west and eastern sides from where different aerosol species such as mineral dust, soot, nitrate, sulfate particles and organics are produced and transported to this region (Srivastava *et al.*, 2012a). The experimental site of the present study is Agartala, situated at the outflow of IGP basin and as a result of this; the region is prone to large amount of contribution due to IGP flow. Thus in situ measurement of black carbon at such station has its own importance. Even though, several studies on short as well as long term properties of EBC and source impact over the Indian region are available (e.g., Satheesh and Ramanathan, 2000; Babu *et al.*, 2002; Nair *et al.*, 2007; Beegum *et al.*, 2009 etc.), the study of EBC over the northeastern part of India is scarce other than that reported long-term properties of EBC from Dibrugarh (Pathak *et al.*, 2010).

In this paper, we present the characteristics of aerosol equivalent black carbon (EBC) at a rural continental site, Agartala, located in the North-Eastern part of India using 2 years (September 2010–September 2012) measurements. The temporal variations of EBC concentration in diurnal and seasonal scale are examined. These variations are explained on the basis of geographical location, changing meteorological conditions, distinct source characteristics and long range transport under favorable conditions. Also Concentration weighted trajectory (CWT) analysis is done to study the advection from various distant locations in different seasons.

**BRIEF DESCRIPTION OF THE OBSERVATIONAL SITE**

The observational site Agartala (23.76°N and 91.26°E), located in the North Eastern part of India (Fig. 1) in the state of Tripura, is a rural and continental site. The continuous measurement of EBC mass concentrations ($M_{BC}$) has been carried out from the premises of Tripura University. The university, situated adjacent to the Agartala-Sabroom National Highway, is about 9 km south from the main city of Agartala, where automobile and vehicular emission are
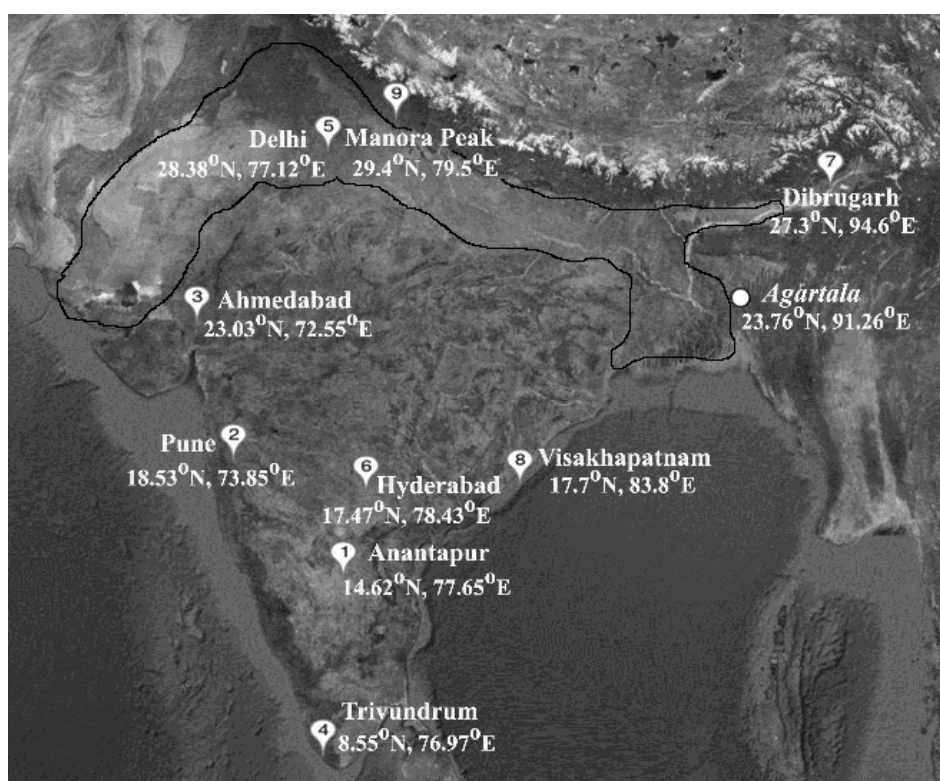


**Fig. 1.** Geographical position (Lat., Long.) of Agartala in the northeastern part of India. The data from the other locations (as shown in the figure) are compared with those observed at Agartala.

the principle source of air pollution. A large number of automobiles run through highway from morning to near-mid-night. In addition, there are several brick kilns around the observational site within 50 km radius.

The observational site and the neighboring northeastern part of India bear, in general, tropical monsoon climate with mild winter, warm, and humid summer. Following climatological fashion, minimum average temperature vary between 5 to 6°C with calm winds during winter months (December–February), while during pre-monsoon (March–May), the weather is hot and humid with the maximum temperature going up to around 36°C. The average annual temperature is 24°C and the average annual rainfall is 2000 mm. The peak rainfall occurs in the month of June–July with mean rainfall of 450 mm. In general the relative humidity is high across the whole year with an average of 81%. However, average relative humidity of 74% is moderately lower in dry season compared to the wet season (June–September) with an average relative humidity of 87%. Figs. 2(a) and 2(b)

show the monthly variation of wind speed, temperature, relative humidity and rainfall during our observational period (September 2010–September 2012), while their monthly mean maximum and minimum values are given in Table 1. Winds are generally very weak, less than 1.5 m/s throughout the whole year showing little variation over the year. The wind speed is minimum in winter with wind speed of 0.2 m/s but it shows relatively higher value of 1.1 m/s in pre-monsoon and monsoon seasons. Monthly mean temperature shows higher value in pre-monsoon and monsoon with highest mean value of 28°C and lower value in winter with lowest mean value of 17°C. The average relative humidity during the observational period is higher (~75%). Seasonal mean rainfall shows maximum value in monsoon and minimum in winter. To study the seasonal variation of EBC concentration, the months of the year are divided into four seasons, namely winter (December–February), pre-monsoon/summer (March–May), monsoon (June–September), and retreating monsoon/post-monsoon (October–November).
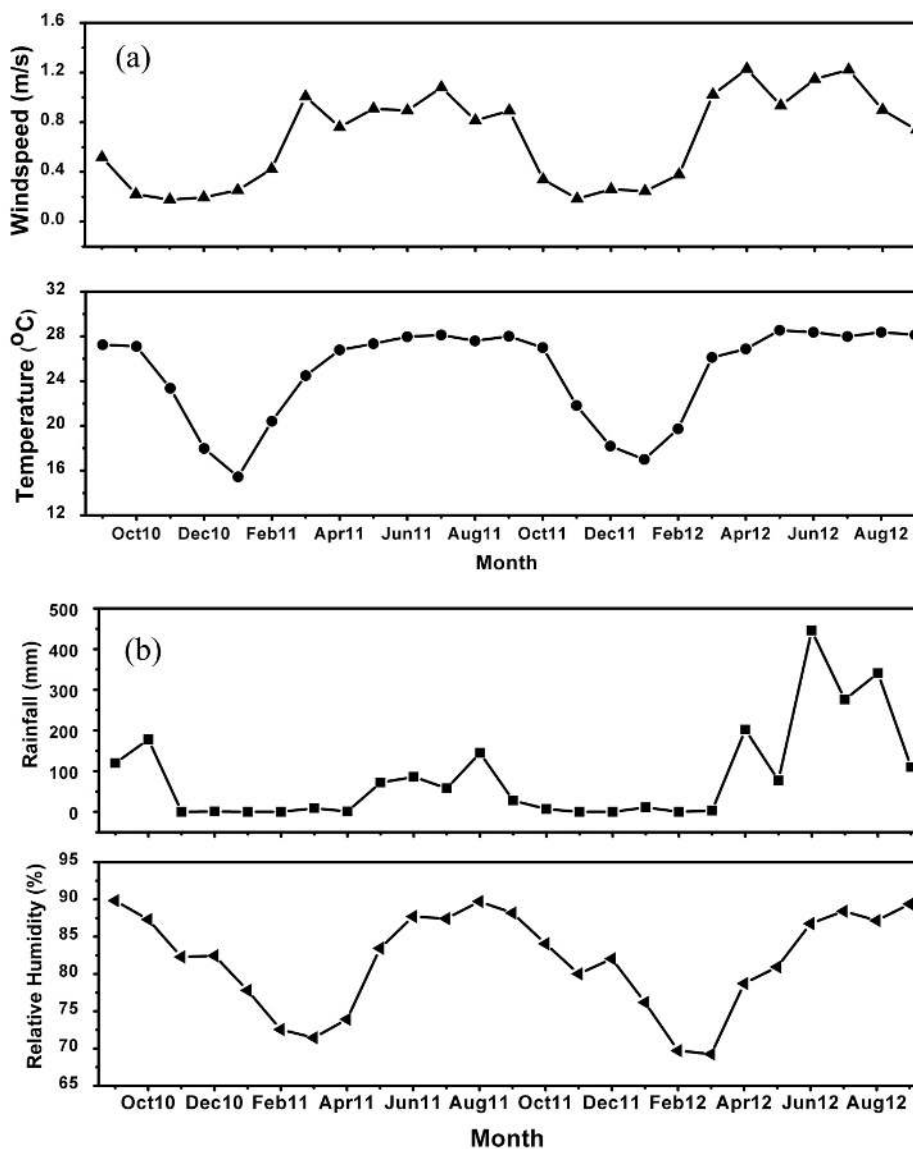


**Fig. 2.** Monthly variation of (a) wind speed (m/s) and temperature (°C) and (b) rainfall (mm) and relative humidity (RH %).

**Table 1.** Seasonal mean values of local meteorological parameters at Agartala during the study period.

| Season | Maximum Temperature (°C) | Minimum Temperature (°C) | Relative humidity (%) | Wind speed (m/s) | Rainfall (mm) |
|---|---|---|---|---|---|
| Winter | 25.6 ± 1.96 | 13.4 ± 1.65 | 76.7 ± 5.07 | 0.29 ± 0.088 | 6 ± 2 |
| Pre-monsoon | 31.9 ± 0.73 | 22.3 ± 1.79 | 76.3 ± 5.61 | 0.98 ± 0.155 | 200 ± 100 |
| Monsoon | 30.8 ± 1.04 | 25.2 ± 1.28 | 88.3 ± 1.19 | 0.91 ± 0.216 | 1000 ± 500 |
| Post-monsoon | 30.2 ± 1.53 | 21.3 ± 2.96 | 83.4 ± 3.08 | 0.23 ± 0.075 | 125 ± 75 |

## INSTRUMENTATION (MEASUREMENT DATA)

Measurements of near-real time EBC mass concentrations were made using a seven channel Aethalometer (model AE-31, Magee Scientific, USA). This is a filter based technique that measures the light attenuation due to particles deposition on to a quartz filter. The instrument aspirates ambient air through an inlet tube connected to a pump. The particles impact on the quartz filter tape, the change in transmittance of which after each collection interval is represented in terms of the mass of EBC. During the present study, the aethalometer was operated at a flow rate of 3.9 L/min; and at a time base of 5 min, on all the days and round the clock. The attenuation measured at 880 nm wavelength is considered standard for EBC mass concentration; as at this wavelength, EBC is the principal absorber of light, while other known aerosol components have negligible absorption (Bodhaine, 1995).

Though the optical attenuation method has shown excellent agreement with other analytic methods (Allen *et al.*, 1999; Im *et al.*, 2001) and has been widely used (Babu *et al.*, 2002; Beegum *et al.*, 2009; Babu *et al.*, 2011), there are several reports available in recent literature on the uncertainties related to the estimation of EBC by aethelometer (e.g., Weingartner *et al.*, 2003; Arnott *et al.*, 2005; Corrigan *et al.*, 2006). From different literature, it is clear that all the available methods for measurement of EBC mass concentration are based on some assumptions that are instrument specific, site specific and also depends on the type of carbonaceous aerosol, and its fraction to the total aerosol mass (Weingartner *et al.*, 2003; Hitzenberger *et al.*, 2006; Moorthy *et al.*, 2007; Nair *et al.*, 2007). So there is no standard method that gives unique value of EBC concentration for a particular location.

The filter-based absorption technique though suffers from various systematic errors (Liousse *et al.*, 1993; Petzold *et al.*, 1997; Bond *et al.*, 1999), there are two major uncertainties in EBC estimations by aethalometer namely shadowing effect, resulting in an underestimation of EBC at higher particles load and multiple scattering effect, resulting in an overestimation of EBC (Weingartner *et al.*, 2003). For accurate determination of EBC mass concentration by aethalometer, the absorption data from the instrument need to be corrected to remove the above mentioned uncertainties and these corrections require collateral measurements for scattering (Collaud Coen *et al.*, 2010). As there is no such simultaneous scattering measurements in our location, we have taken into consideration two correction factors C and R suggested by Weingartner *et al.* (2003). In our measurements, we have used the correction factor C of 2.14 and R factor of 1 derived from comparison with other techniques that

are in agreement with the absorption cross section of 16.62 m²/g (given by manufacturer) at 880 nm as used by Nair *et al.* (2007) and Pathak *et al.* (2010). The uncertainties due to changes in sampling condition and instrument noise is reduced by using long averaging period ( Moorthy *et al.*, 2007, Dumka *et al.*, 2010 and Kumar *et al.*, 2011). As we have used very long (monthly and seasonal) averages of EBC, such long range averaging have given an advantages of reduction in uncertainties originating from instrumental noise and other sampling conditions like humidity etc. From inter comparison between different techniques; it was found that in spite of site-specific and instrument-specific instantaneous value of EBC, the average concentration obtained by various techniques tend to agree within the instrumental uncertainties for aged (away from strong sources) aerosols (Hitzenberger *et al.*, 2006; Moorthy *et al.*, 2007; Dumka *et al.*, 2010). As there are no such prominent and strong local sources of fresh EBC near to our observational site, the concept of aged aerosol is well applicable to our site also. Applying the above mentioned correction approaches we have tried our best to minimize the uncertainty in EBC concentration data, derived from absorption data by aethelometer. Still we acknowledge that the data might have some systematic uncertainties as we have no simultaneous scattering measurement.

## RESULTS AND DISCUSSION

### Diurnal Variation

Diurnal variations of seasonal mean values of EBC mass concentrations are shown in Fig. 3 (left panel). A significant diurnal variation in EBC mass concentration with two prominent peak is observed during the post monsoon, winter and summer periods, which is absent during monsoon with very low magnitude of EBC. The morning peak in EBC occurs around 7:00–8:00 IST (Indian Standard Time), which then decreases rapidly to reach its low level around afternoon (13:00–16:00 IST) and thereafter increases more rapidly to reach its second prominent peak during early night around 19:00–21:00 IST. The early evening peak value of EBC mass concentrations during post monsoon, winter and pre-monsoon (summer) months are found to be = 21.8 ± 11.5, 36.8 ± 9.3 and 16.1 ± 7.5 μg/m³, respectively.

The observed diurnal variation is attributed to the boundary layer dynamics, though variations of emission sources may also be partly responsible for this. The sharp peak occurring between 07:00 and 08:00 IST after sunrise arises from fumigation effect in the boundary layer (Stull, 1998, Babu and Moorthy 2002; Beegum *et al.*, 2009), which is responsible for bringing the aerosols and pollutants to
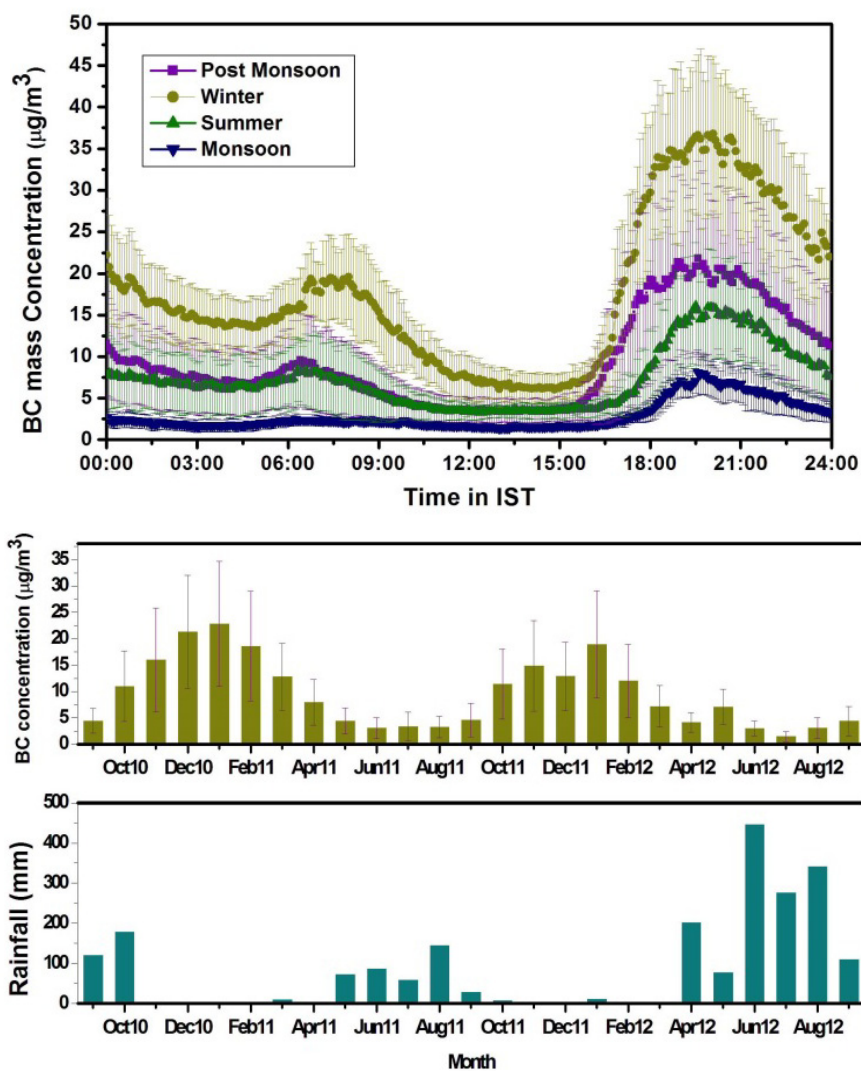
**Fig. 3.** Diurnal variation of seasonal mean values of EBC mass concentrations (upper panel) and monthly variation of EBC mass concentrations and rainfall (lower panel) during September 2010 and September 2012.

the surface from the residual nocturnal boundary layer after sunrise. As the day advances, Atmospheric Boundary Layer (ABL) becomes deeper and the increased solar heating leads to increase turbulent affect which thoroughly mix and redistribute aerosols into higher heights. This leads to faster dispersion and hence dilution of aerosol concentration around the afternoon till evening 13:00 to 16:00 IST. The diurnal variation of wind speed, which becomes higher at the afternoon than the morning and night hours, may also influence the observed low concentration of EBC in afternoon period (Srivastava *et al.*, 2012b).

In the evening hours, the decreased boundary layer mixing and shallow stable boundary layer (Beegum *et al.*, 2009) causes the aerosols to get trapped near the surface and the confinement leads to an increase in the concentration near the surface attaining its maximum value at night. Further, the nocturnal boundary layer (NBL) is shallower than its day time counter part by a factor of about 3 (Kunhikrishnan *et al.*, 1993). Also, the reduced ventilation coefficient due to lower wind speed at night leads to confinement of aerosol

and consequently an increase in its concentration during early night (Sreekanth *et al.*, 2007). As the night progresses, the decrease in local anthropogenic activities and traffic emission results in a reduction in basic generation and consequently EBC concentration decreases. The loss of particle closer to the surface by sedimentation also assists this reduction of EBC concentration at night (Babu and Moorthy, 2002; Ramachandran and Rajesh, 2007).

Apart from ABL dynamics, the morning hour local anthropogenic activities can also be responsible factor for morning peak in diurnal variation. But as our observational site is not highly industrialized and not a densely populated city, located 9 km away from the main city, the local source affect may not be significant during morning hours. Though the national highway passes near the observational site, yet the traffic density peak during office hours (9:00 IST), which is also not much higher like other cities of India. However, some other anthropogenic activities that contribute to the EBC concentration for the morning peak may be the wood, bamboo and cow-dung combustion for

cooking by the residents in the less populated nearby villages. In addition, the burning of dry leaves, grasses, shrubs and bamboos for heating purpose in the winter contribute to the local source of EBC concentration in winter.

On the other hand, the local traffic activity reaches its maximum during the period 17:00 IST to 19:00 IST after office hour. Also the burning of fuels (both fossils and biofuels) is increased in the evening for cooking and other household activities in the adjacent residential areas. So, significant emissions from the local traffic and the burning of fuels would be contributing to the sharp rise in EBC concentration in the evening. In addition, the burning of wood, dry leaves and shrubs at evening time during cold winter months for warming contributes to the evening large peak like the morning peak. All these local factors, in addition to shallower nocturnal boundary layer and lower wind speeds in the evening cause a rapid reduction in the ventilation effects and consequently confining the EBC aerosol leading to the secondary peak. There is no diurnal variability in EBC during monsoon months, as the magnitude of EBC concentration itself is very low.

### Seasonal Variation

Fig. 3 (upper panel) shows the monthly mean EBC mass concentrations, with vertical bars as standard deviations of the respective mean, with minimum value of ~3.25 µg/m$^3$ in August, 2011 and maximum value of ~22 µg/m$^3$ in January, 2011. The seasonal mean EBC mass concentrations are 17.8 ± 9.2 µg/m$^3$, 7.3 ± 3.6 µg/m$^3$, 2.8 ± 1.7 µg/m$^3$ and 9.5 ± 5.5 µg/m$^3$ in winter, pre-monsoon, monsoon and post-monsoon respectively. The annual average EBC concentration is 9.35 ± 4.9 µg/m$^3$. The EBC concentration in winter is very much higher (~90%) than the annual average EBC concentration, while EBC concentration decreases by 69% from the annual average value in monsoon.

The seasonal variation in EBC mass concentration could mainly be related to the seasonal differences in the depth of ABL as well as differences in sources and strength in different seasons. The stable ABL, due to low wind speed and hence low surface convection, opposes aerosol particles to disperse much into atmosphere and it gets trapped near the boundary layer showing the high EBC concentration in winter (Srivastava *et al.*, 2012b). There are also several other potential sources for increase in EBC concentration over the site during winter like burning of agricultural field residue, dry leaves, shrubs etc. in nearby location and wood combustion and biomass burning for cooking and warming in the nearby villages and residential houses in winter season.

The decrease in EBC from winter to summer may be associated with the increase in ventilation coefficient (V$_C$) (Beegum *et al.*, 2009) with the change in solar position and difference in the day time ABL associated with change in temperature and stronger winds. The EBC concentration is significantly reduced during monsoon season associated with the wash out of EBC due to precipitation and scavenging effect of rainfall (Bano *et al.*, 2011). The monthly variation of rainfall in the bottom panel of Fig. 3 also clearly shows that the low values of EBC are associated with the higher amount of rainfall. Also the temperature is comparatively

higher in monsoon, consequently a relatively higher degree of turbulence and higher thickness of mixed boundary layer (Stull, 1998) results in more dispersion and thereby reduced EBC concentration in monsoon season (Baxla *et al.*, 2009). During post monsoon period the EBC aerosol starts rebuilding. Apart from the ABL and local source effect, the long range transport also contributes to the seasonal differences, which are discussed in a subsequent section.

The EBC mass concentrations measured at our location are compared with those reported for different locations from various parts of India (shown in Fig. 1) and presented in the Table 2. The annual mean EBC concentration at Tripura (~9.35 µg/m$^3$) during September 2010 to September 2012 is comparable to those reported over Delhi, Dibrugarh, Ahmedabad and Hyderabad, but higher than those reported over Trivandrum, Vishakapatnam, Anantapur, Manora peak and Pune. However, seasonal mean values of EBC at Tripura are consistently lower than those at Delhi in all seasons. As Delhi is highly industrialized, densely populated and a city of high traffic density, the higher concentration over Delhi than Tripura may be attributed to the greater influence of anthropogenic sources such as vehicular and industrial emissions in the region (Bano *et al.*, 2011).

On the other hand, EBC mass concentrations in various seasons at Agartala show consistently very high values, unlike to those at Anantapur. Although, the EBC concentrations at Agartala during monsoon is similar to those at Ahmedabad and Trivandrum, the EBC concentrations at Agartala during other three seasons are about 3 times higher than those observed at these two stations. The seasonal mean EBC concentrations at Tripura during all four seasons are a factor of 2 higher than those observed at Pune and Vishakapatnam. It is interesting to note that during winter, EBC concentrations at Agartala are higher than all other locations in India and it is due to shallow boundary layer, higher ΔT (differences between maximum and minimum temperatures) and transport of EBC from other polluted regions under favorable wind conditions.

Comparing EBC concentrations at our location with those at Dibrugarh, another station from North East, it is found that the diurnal and seasonal patterns are nearly similar at these two rural sites, being not subjected to the influence of highly local and seasonal anthropogenic activities, though an oil refinery is situated near Dibrugarh and some small brick factories are located within 50 km radius of our observational site at Agartala. The similar high EBC concentration in winter may also be associated with the foggy and hazy condition during the winter period in this two site (Pathak *et al.*, 2010). These similar EBC concentration in all seasons at these two rural sites may be due to similar local meteorological condition in these two stations and long range transport in different seasons as these two station are under the influence of long range transport from IGP basin.

### Ångström Absorption Coefficients

Several attempts were made during last decade to measure the absorption property of aerosols using different techniques; uncertainties still remain the same because of the lack of

**Table 2.** Black Carbon Mass Concentrations Measured at Various Locations in India.

| Location | Type of location | Observation period | EBC Concentration (µg/m³) | | | | | Reference |
|---|---|---|---|---|---|---|---|---|
| | | | Winter | Pre monsoon (Summer) | Monsoon | Post monsoon | Mean EBC ± σ/ EBC mass range | |
| Anantapur (14.62°N, 77.65°E) | Semi-arid, Rural | Jan.–Dec. 2010 | 5.05 ± 0.51 | 3.77 ± 1.23 | 1.55 ± 0.51 | 2.33 ± 0.82 | 3.03 ± 0.27 | Reddy *et al.* (2012) |
| Anantapur (14.62°N, 77.65°E) | Semi-arid, Rural | Aug. 2006–Jul. 2007 | 3.31 ± 0.61 | 2.17 ± 0.51 | 1.04 ± 0.47 | 1.55 ± 0.35 | 1.97 ± *0.12* | Kumar *et al.* (2011) |
| Pune (18.53°N, 73.85°E) | Urban, Industrialized | Jan.–Dec. 2005 | 7.38 | 3.25 | 1.31 | 6.04 | 4.1 | Safai *et al.* (2007) |
| Ahmedabad (23.03°N, 72.55°E) | Urban, Industrialized | Sep. 2003–Jun. 2005 | 5 (Jan. 2004) | | 0.8 (Jul.2004) | | 0.21–10.2 | Ramachandran and Rajesh (2007) |
| Trivundrum (8.55°N, 76.97°E) | Coastal, Semi urban | Jan. 2000–Dec. 2003 | 5.68 ± 0.021 | 2.62 ± 0.014 | 2.01 ± 0.006 | 3.46 ± 0.019 | 2–6 | Moorthy *et al.* (2007) |
| Delhi | Urban, Industrialized | 2001–2002 | 26.1 | 13.9 | 12.2 | 23.3 | 12–26 | Rai *et al.* (2002) |
| Delhi (28.38°N, 77.12°E) | Urban, Industrialized Semi-arid | Jan.–Dec. 2006 | 25.5 | 9.4 | 7.7 | 13.7 | 14.75/(5.7–30.3) | Bano *et al.* (2011) |
| Hyderabad (17.47°N, 78.43°E) | Urban Semi-arid | Jan.–Dec. 2003 | 10.0 (Nov.–Apr.) | | 4.0 (Jun.–Oct.) | | 10.0–4.0 | Latha and Badrinath (2005) |
| Ahmedabad (23.03°N, 72.55°E) | Urban | 2003–2005 | 5.5 ± 2.8 | 2.2 ± 1.0 | 1.5 ± 0.8 | 7.3 ± 3.7 | 1.5–7.3 | Ganguly *et al.* (2006) |
| Dibrugarh (27.3°N, 94.6°E) | Rural, Continental | Jun. 2008–May. 2009 | 16.3 ± 1.4 | 7.5 ± 1.5 | 3.4 ± 0.9 | 10.9 ± 3.9 | 3.4–16.3 | Pathak *et al.*(2010) |
| Visakhapatnam (17.7°N, 83.8°E) | Coastal, Semi urban | Dec. 2005–Sep. 2006 | 8.01 | 3.33 | 1.67 | 0.43 | 0.4–8 | Sreekanth *et al.* (2007) |
| Manora Peak (29.4°N, 79.5°E) | Rural ,High altitude | Jun. 2006–May 2007 | 1.2 ± 0.3 | 1.5 ± 0.2 | 0.6 ± 0.2 | 1.4 ± 0.1 | 0.4–1.8 | Srivastava *et al.* (2011) |
| Minicoy (8.3°N,73.04°E) | Remote, island | Feb. 2006–Mar. 2007 | 0.8 | | 0.1 | | | Vinoj *et al.* (2008) |
| Ahmedabad (23.03°N, 72.05°E) | Urban, Industrialized | Jan.–Dec. 2008 | 11.6 ± 2.9 | 3.9 ± 2.5 | 2.1 ± 0.8 | 10.9 ± 1.5 | | Ramachandran and Kedia (2010) |
| Agartala, Tripura (23.76°N, 91.26°E) | Rural ,Continental | Sep. 2010–Sep. 2012 | 17.8 ± 9.2 | 7.3 ± 3.6 | 2.8 ± 1.7 | 9.5 ± 5.57 | 9.35 ± 4.9 | Present study |

accurate measurements (Sato *et al.*, 2003). The raw absorption coefficient ($\sigma_{ATN}$) of aethalometer is estimated using the change in attenuation measured using the aethalometer as,

$$\sigma_{ATN}(\lambda) = \frac{\Delta ATN(\lambda)}{\Delta t}\frac{A}{Q} \qquad (1)$$

where A is the filter spot area, Q is the volume of air sampled through the filter during time interval $\Delta t$ and $\Delta ATN (\lambda)$ is the change in attenuation at the wavelength $\lambda$ due to particles deposition on the filter during $\Delta t$. It is well known that, raw absorption coefficient ($\sigma_{ATN}$) generally differs from the true absorption coefficient ($\sigma_{abs}$) because of the inherent problems associated with the technique (Weingartner *et al.*, 2003; Schmid *et al.*, 2006). The most significant factors contributing to this are (*i*) multiple scattering of light at the filter fibers enhances the optical path length leading to an overestimation of $\sigma_{abs}$, (*ii*) enhanced absorption of scattered light with increasing filter loading reduces the optical path length. Using the raw absorption coefficient ($\sigma_{ATN}$) of the aethalometer at different wavelengths, the Ångström absorption coefficients [$\sigma_{abs}(\lambda)$] at the operational wavelengths ($\lambda$) are calculated by using the Eq. (2)

$$\sigma_{abs}(\lambda) = \frac{\sigma_{ATN}(\lambda)}{CR} \qquad (2)$$

The parameters C and R are correction factors for minimizing the inherent uncertainty associated with Aethalometer, arising from multiple scattering of light in the filter matrix and the change in the optical path length due to successive aerosol loadings (as already mentioned in Instrumentation section).

The dependence of aerosol light absorption on wavelength is parameterized using a power law relationship (Kirchstetter *et al.*, 2004):

$$\sigma_{abs}(\lambda) = K\lambda^{-\alpha_{abs}} \qquad (3)$$

where $\sigma_{abs}(\lambda)$ is the spectral absorption coefficients and $\alpha_{abs}$, the Angstrom absorption exponent, is a measure of spectral dependence of aerosol absorption and K is a constant. From Eq. (3) $\alpha_{abs}$ is determined by performing linear least square fit of ($\sigma_{abs}$) and ($\lambda$) in log-log scale. It was reported that aerosols produced from biomass burning shows stronger wave length dependence ($\lambda^{-2}$) in absorption with $\alpha_{abs} \sim 2$; whereas a weaker wavelength dependence ($\lambda^{-1}$) with $\alpha \sim 1$ is exhibited by aerosols produced from fossil fuel burning such as motor vehicle exhausts etc. (Kirchstetter *et al.*, 2004). Several other researchers such as Jacobson (2000), Bond (2001), Bergstrom *et al.* (2002) have also shown that atmospheric aerosol mixtures in which absorption is mainly due to EBC, exhibit a weak spectral dependence ($\lambda^{-1}$).

Fig. 4 shows the spectral variation of absorption coefficients at different seasons. It shows that wavelength dependence of $\sigma_{abs}$ remains nearly same in all the seasons; however the values $\sigma_{abs}$ are highest in winter and lowest in monsoon respectively for all wavelengths. These seasonal differences in $\sigma_{abs}$ are related to the sources and their strengths being changed seasonally, as discussed in the previous section, associated with the change in aerosol type due to change in seasonal advection pathways and change in local meteorological conditions with seasons (Gogoi *et al.*, 2013). Thus, with an aim to identify the wavelength dependence of $\sigma_{abs}$ and hence source contribution, $\alpha_{abs}$ is determined for all months. Fig. 5 (top panel) shows month wise variation of $\alpha_{abs}$ during the observational period. The seasonal variation of $\alpha_{abs}$ in different seasons may be used to quantify these relative changes in absorption characteristics of aerosols for different seasons (Ganguly *et al.*, 2006). It is seen that the mean value of $\alpha_{abs} \sim 1$ in all seasons with highest value of 1.13 in Mar 2012 and lowest ($\sim 0.91$) in September 2012. By some sample calculations for externally mixed, internally mixed and shell-core configurations of BC, Jacobson (2000) showed that in spite of difference in calculated absorption coefficient, the wavelength dependence remains nearly similar for different cases for the spectral region of 0.45–
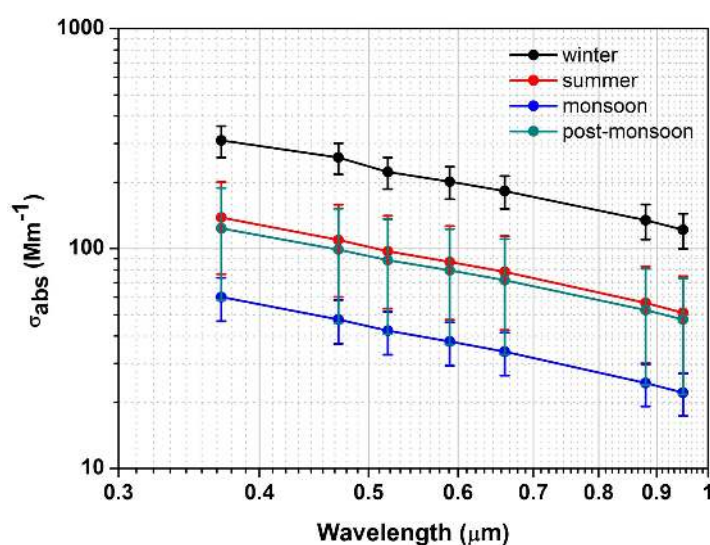


**Fig. 4.** Spectral variation of aerosol absorption coefficients ($\sigma_{abs}$) at different seasons.
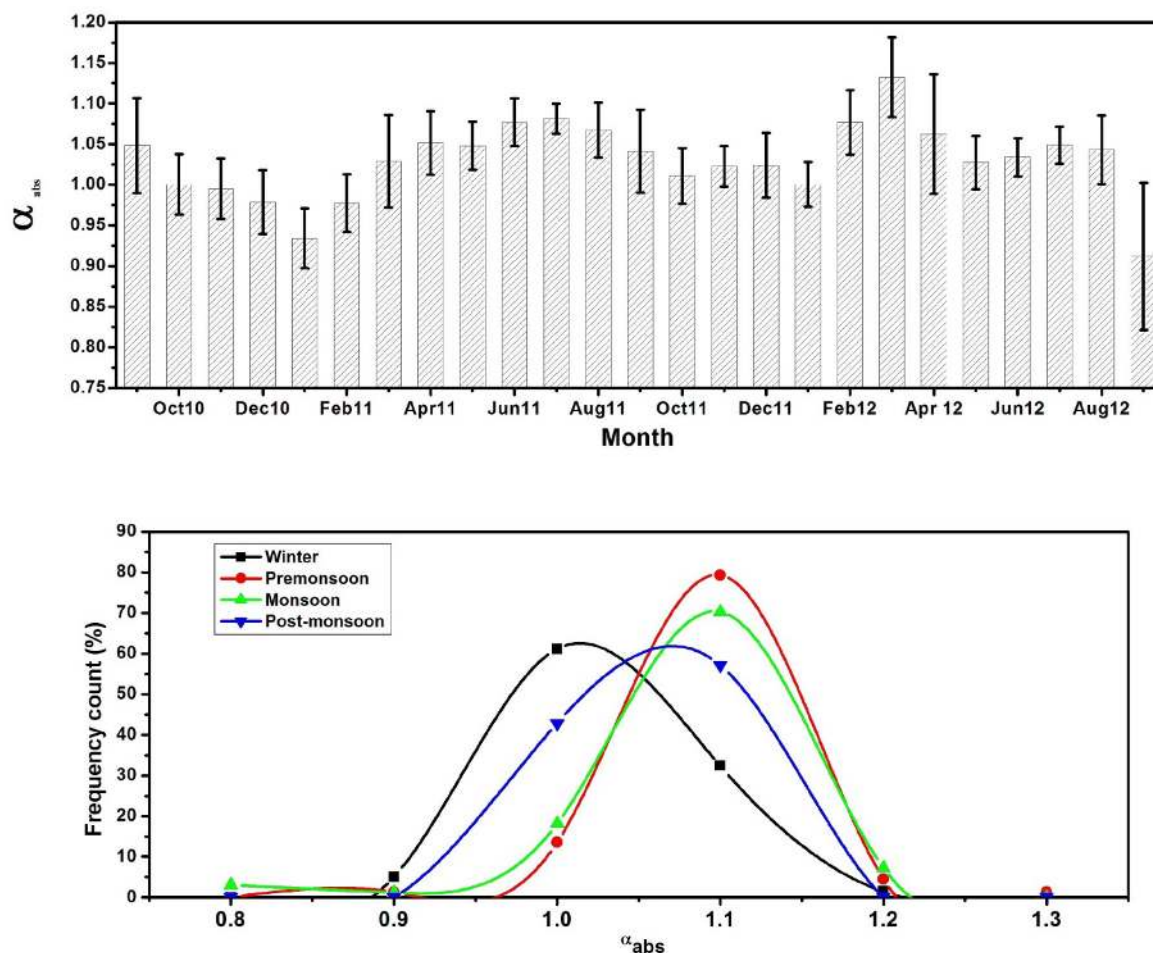
**Fig. 5.** Variation of the monthly mean values of $\alpha_{abs}$ (top panel) and its frequency distribution at different seasons (bottom panel).

0.1 μm. As $\alpha_{abs}$ can be an indicator of aerosol composition (Park *et al.*, 2006; Ajtai *et al.*, 2010), the almost similar wavelength dependence ($\alpha_{abs} \sim 1$) in all seasons at Agartala possibly indicates the presence of aerosol compositions originating from a common source in all seasons. The above discussions thus indicate the signature of fossil fuel combustion being the dominating source of EBC in this region. At the same time, the slight increase in the values of $\alpha_{abs}$ ($> 1.0$) during the pre-monsoon months (March, April and May) could be associated with the biomass burning aerosols, being prominent over the northeastern region during this period, however the experimental site is not significantly affected.

With a view to examining the contribution of different sources to EBC concentration in different seasons in our location, frequency distributions of $\alpha_{abs}$ for different seasons are shown in Fig. 5 (bottom panel). The figure shows that pre-monsoon and monsoon seasons are identified with higher value of $\alpha_{abs}$ with 80% and 70% values of $\alpha_{abs}$ in the range of 1.0–1.1 respectively. On the other hand, in winter 61% values of $\alpha_{abs}$ lies in the range of 0.9–1.0 and 57% values of $\alpha_{abs}$ lies in the range of 1.0–1.1 in post monsoon. This confirms again the mild influence of the biomass burning events on aerosol absorption over the northeastern

region leading to slightly higher values $\alpha_{abs}$ during pre-monsoon season. Although the EBC concentration in our location significantly differs with seasons, the absorption property of EBC aerosols remains the same in all seasons whether it is of local origin or advected from distant sources.

**SOURCE APPORTIONMENT**

With a view to examining the influence of different sources in variation of EBC concentration with seasons, Concentration Weighted Trajectory (CWT) analyses are performed for each season following the details given in Gogoi *et al.* (2011), Vinoj *et al.* (2010) and shown in Fig. 6. The trajectory clusters show that the mean pathways differ with seasons. The winter is characterized by dominant trajectory clusters from continental origin while trajectory clusters gradually shifts from continental to continental plus oceanic origin in pre-monsoon. Trajectory clusters traversing the marine origin dominate in monsoon and again it becomes mixed, i.e. continental plus oceanic origin in post monsoon. The influence of advection from IGP and continental regions in winter, showing weaker spectral dependence (mean $\alpha_{abs} = 0.99$) ensures the dominance of fossil fuel originated EBC in winter. During monsoon, the
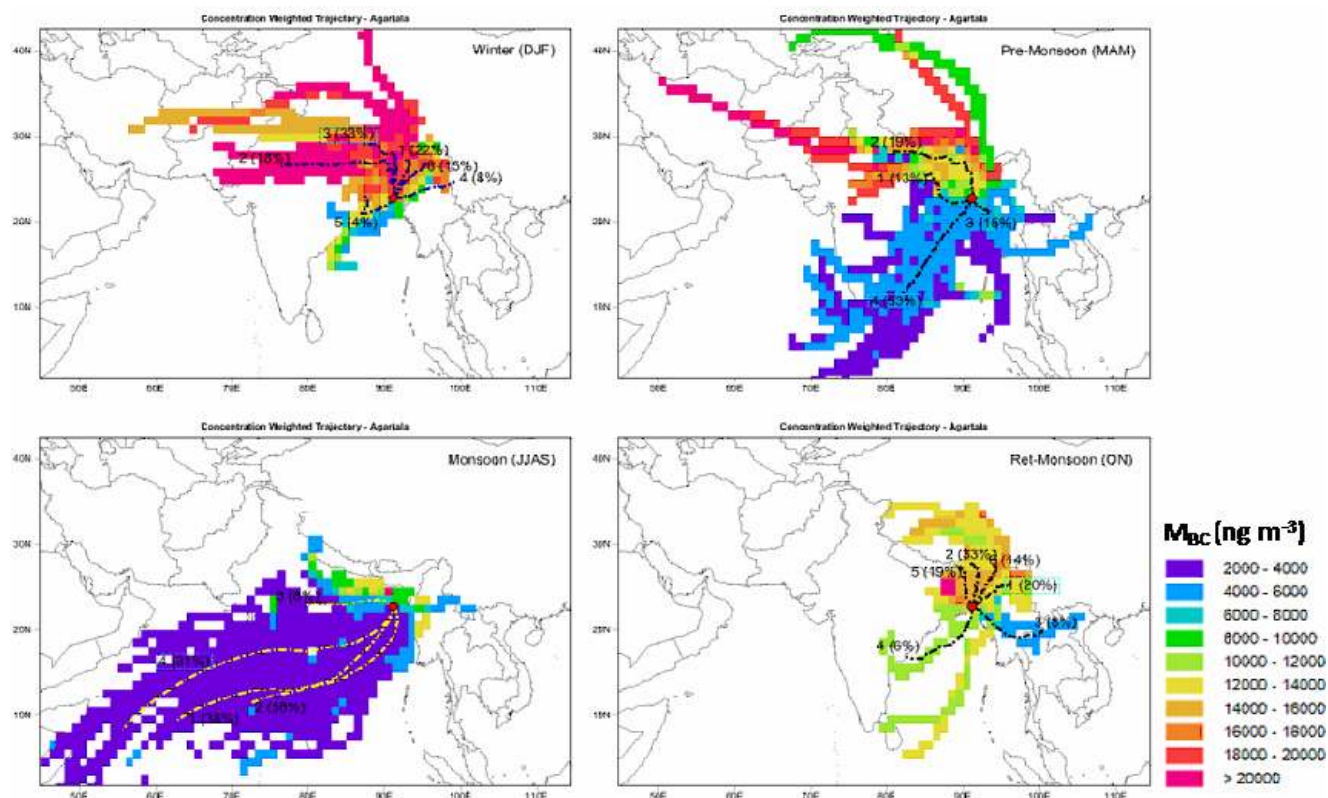
**Fig. 6.** Cluster of trajectories and CWT map of EBC concentrations at different seasons.

trajectory clusters traverse mainly the oceanic region brings cleaner air, leading to low EBC concentration in this season. The weak spectral dependence of aerosol absorption (mean $\alpha_{abs}$ = 1.03) in monsoon, confirms the EBC is fossil fuel originated and completely of local origin. The washout by rain and stronger wind leads to such low EBC concentration in monsoon. Similarly, the weaker spectral dependence of aerosol absorption during pre-monsoon and post-monsoon seasons (mean $\alpha_{abs}$ 1.04 and 1.0 respectively) ensures combustion of fossil fuel as origin of EBC in our location. As the local sources gradually strengthens in these seasons due to low wind speed and shortage of rainfall, EBC is partially contributed from local sources, though advections from distant sources of IGP and continental regions also play a part in enhancement of EBC as evident from trajectory clusters.

**CONCLUSIONS**

The present work addresses the diurnal and seasonal variation of EBC concentration during two year period from September 2010 to September 2012 in Tripura, a rural continental site in the North-Eastern part of India. The EBC concentration shows well defined diurnal and seasonal variability. The diurnal variation of EBC concentration exhibits dual peaks, one in the morning and the other at night. The seasonal variation of EBC concentration shows maximum concentration in winter followed by post monsoon seasons and pre-monsoon seasons and low concentration of EBC are observed in monsoon months. The EBC mass

concentration was found to be 17.8 ± 9.2 μg/m³ in winter and 2.8 ± 1.7 μg/m³ in monsoon. The seasonal variations are mainly associated with variation of source strength with local meteorological conditions and advection from distant sources. The diurnal variations are mainly due to boundary layer dynamics, although the local anthropogenic activities play partial role in such diurnal variability. From wavelength dependence of EBC absorption, it is found that EBC in our observational site is mainly originated from fossil fuel combustions. CWT analysis shows that advection from IGP and continental regions partly contribute to EBC concentration in winter, pre-monsoon and post monsoon seasons. But EBC in monsoon is completely of local origin as trajectory clusters are mostly from marine origin bringing clean air in monsoon. From the comparison of EBC concentration of our location with other location in India, it is observed that EBC concentration at Tripura is comparable to that at Dibrugarh, another rural location in northeast India. The EBC concentration at Tripura is higher than that of the most of urban, rural and coastal observational site in India except Delhi, a highly industrialized urban location in India.

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