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Aerosol black carbon characteristics over a high-altitude Western Ghats location in Southern India

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Abstract. Aerosol black carbon (BC) mass concentrations were continuously monitored over a period of 2 years (April 2010 to May 2012) from a high-altitude location Ooty in the Nilgiris Mountain range in southern India to characterize the distinct nature of absorbing aerosols and their seasonality. Despite being remote and sparsely inhabited, BC concentrations showed significant seasonality with higher values ($\sim 0.96 \pm 0.35\,\mu g\,m^{-3}$) in summer (March to May), attributed to increased vertical transport of effluents in the upwind valley regions, which might have been confined to the surrounding valley regions within the very shallow winter boundary layer. The local atmospheric boundary layer (ABL) influence in summer was further modulated by the long-range transported aerosols from the eastern locations of Ooty. During monsoon (June–August), the concentrations were far reduced ($\sim 0.23 \pm 0.06\,\mu g\,m^{-3}$) due to intense precipitation. Diurnal variations were found conspicuous mainly during summer season associated with local ABL. The spectral absorption coefficients (α_{abs}) depicted, in general, flatter distribution (mostly < 1.0 for more than 85 % of daily mean values), suggesting the relative dominance of fossil fuel combustion, though showed marginal seasonal change with higher values of α_{abs} in summer.

Keywords. Atmospheric composition and structure (aerosols and particles)

1 Introduction

Aerosol black carbon (BC), produced mainly due to incomplete combustion of fossil fuel or biomass, is amongst the strongest contributors to the radiative warming of the atmosphere (Marinoni et al., 2010), through its strong absorption over a wide wavelength range (from UV to IR). They can heat the air, alter atmosphere stability, large-scale circulations and cloud albedo by changing the hygroscopicity of cloud condensation nuclei. BC aerosols are inert in nature as a result of predominant sub-micron size and chemical structure. Being in the fine size range (median diameters in the range 100–200 nm), they bear a long atmospheric residence time, thereby leading to deterioration of air quality and health hazards as easily respirable (Janssen et al., 2012). In addition, BC-containing particles are also associated with adverse effects such as crop yields, contaminating building materials and adversely impact terrestrial and aquatic ecosystems (Cao et al., 2009).

During recent years, BC has attracted special attention mainly because of its contribution to radiative warming of the atmosphere (Haywood and Shine, 1997; Myhre et al., 1998; Jacobson, 2001, 2002). The Intergovernmental Panel on Climate Change (IPCC, 2007) has estimated that the global mean clear-sky radiative forcing of BC is 0.23 (± 0.25) $W\,m^{-2}$, which is approximately half the value of methane, the second most important greenhouse gas after carbon dioxide. The developing world, especially the Asian region with its large population, rapidly growing industrialization and diverse living habitats, is believed to be one of the hotspots of carbonaceous aerosols (Oshima et al., 2012; IPCC, 2007). However, large gap areas still exists

geographically. In this context, characterization of aerosol BC over different geographic locations of India assumes importance. It has been reported that biomass burning and fossil fuel combustion contribute ∼ 49 % of the total fine mode aerosol burden over the Indian sub-continent (Gabriel et al., 2002), making the characterization of BC aerosols more important over distinct geographic locations of the country.

In view of the above, continuous measurement of aerosol BC was initiated from Ooty, a high-altitude location in Western Ghats of southern India in the Nilgiris Mountain range, to understand the aerosol absorption properties over this remote environment, and the changes in the spectral absorption associated with the changes in dominant source types with subdued human interference. The information of BC characteristics over this high-altitude location is also important in understanding the consequences of regional weather and climate implications. In this paper, we present the results of aerosol BC measurements carried out for the period from April 2010 to May 2012 to understand the absorption characteristics of BC at the high-altitude site.

Figure 1. Geographical position of high-altitude location Ooty in Western Ghats of southern India in the Nilgiris Mountain range.

2 Experimental details

2.1 Site description

The study area, Ooty (11.4° N, 76.7° E, 2520 m a.m.s.l.; Fig. 1), located in the district of the Nilgiris Mountain range in Indian state of Tamil Nadu, represents a fresh, clean and pleasant environment with highly subdued human activity. Dense forests, lofty mountains, extensive tea and coffee plantation and sprawling grasslands characterize the location. The Nilgiris Hills form a part of a larger chain of mountains known as the Western Ghats along the western side of India, which is one of the eight hottest hotspots of biological diversity in the world. As of 2011 India census, the Nilgiris district had population of 735 394, of which 88 430 belonged to Ooty town.

2.2 Instrumentation, database and analysis

Continuous measurements of BC have been carried out from the ARFINET observatory, located at a distance of ∼ 8 km from the main town of Ooty using a seven-channel aethalometer (Model AE-31 of Magee Scientific, USA). Aethalometer is a field rugged instrument extensively used across the aerosol research community for continuous measurements of ambient BC mass concentration over a variety of environments (e.g. Hansen et al., 1984; Novakov et al., 2003; Moorthy et al., 2008; Babu et al., 2011a; Gogoi et al., 2014). The instrument measures attenuation of light beam at seven different wavelengths, namely 370, 470, 520, 590, 660, 880 and 950 nm, transmitted through the aerosols deposited continuously on a quartz fibre filter tape (Hansen et al., 1984). The difference in light transmission through the particle-laden sample spot and a particle-free reference spot of the filter is used to compute the absorption coefficient, which is then converted into "equivalent BC mass" concentration using factory-set wavelength-dependent calibration factors (http://mageesci.com/Aethalometer). Observation at 880 nm wavelength is considered standard for BC measurement, as BC is the principal absorber of light at this wavelength, whereas other aerosol components have negligible absorption at this wavelength.

At Ooty, the aethalometer was operated under 50 % maximum attenuation settings (to keep the loading at a low level), at a standard mass flow rate of 4 L min^{-1} and time base of 5 min, on all the days and around the clock. However, it is important to note that the mass flow rate of 4 L min^{-1} is applicable under standard temperature ($T_0 \sim 293$ K) and pressure ($P_0 \sim 1013$ hPa) conditions. As the ambient pressure at Ooty is lower than the standard conditions, the measured BC values were corrected (e.g. Moorthy et al., 2004) for its pressure. The true BC mass concentration (M_{BC}) is thus calculated as

$$M_{BC} = M^*_{BC}\left[\frac{P_0 T}{P T_0}\right]^{-1}, \quad (1)$$

where M^*_{BC} is the instrument-measured raw mass concentration of BC at ambient conditions, P_0 and P are the standard and ambient pressure and T_0 and T are the corresponding temperatures. Details of the aethalometer principle, operation, uncertainties involved and error budget are reported in Weingartner et al. (2003), Arnott et al. (2005) and Nair et

al. (2008). In general, the instrumental uncertainty of the aethalometer ranges from 50 % at 0.05 µg m^{-3} to 6 % at 1 µg m^{-3} (Corrigan et al., 2006).

Aerosol absorption coefficients (σ_{abs}) were estimated from the raw attenuation data of the aethalometer as a function of λ, for each set of measurements as

$$\sigma_{abs}(\lambda) = \frac{1}{CR} \cdot \left(\frac{\Delta ATN(\lambda)}{\Delta t} \frac{A}{Q} \right), \quad (2)$$

where A is the filter spot area, Q the volumetric flow rate and $\Delta ATN(\lambda)$ is the change in attenuation at the wavelength λ due to particle load on the filter media during the time interval Δt. There are two major uncertainties in the estimation of σ_{abs} due to the effect of multiple scattering in the filter papers and the shadowing effects by the collected aerosol particles (Weingartner et al., 2003; Arnott et al., 2005; Corrigan et al., 2006). The parameters C and R are correction factors for minimizing the inherent uncertainty associated with multiple scattering of light in the filter matrix and the change in the optical path length due to successive aerosol loadings. The correction for these uncertainties was done following Weingartner et al. (2003) incorporating values of $C = 2.14$ and $R = 1$.

The database collected using aethalometer for the period from April 2010 to May 2012 is used in the present study. Supplementary daily mean meteorological data were obtained from the Horticultural Research Station, Tamil Nadu Agricultural University, Ooty for representative meteorological information at the high-altitude western part of the country. The research station is located in the Nilgiris, the queen of hills at an altitude of 2240 m above mean sea level (a.s.l.), at nearly the same altitude of the measurement site (2520 m a.s.l.) at an aerial distance of about 1 km southwest.

3 General meteorology

The general meteorological conditions that prevailed over Ooty are characteristic of a subtropical highland climate. Despite its location in the tropics, Ooty generally features pleasant mild conditions throughout the year in sharp contrast to most parts of South India. However, night time is typically chilly in the months of January and February. The monthly mean values of temperatures are relatively consistent throughout the year; with average high temperatures ranging from about 17 to 20 °C and average low temperatures lying between 5–12 °C. The average precipitation is 1250 mm annually, with a markedly drier season from December through March. For the measurement period, the temporal variations of meteorological parameters (temperature, relative humidity and rainfall) are shown in Fig. 2, while that of wind speed and wind direction are shown in Fig. 3.

As can be seen from Fig. 2, the monthly temperature reached maximum value (∼ 20–25 °C) during the summer (March to May) and a minimum (∼ 15–17 °C) during monsoon (June to August). The relative humidity was generally high (> 50 %) throughout the period of observation. Seasonal rainfall was higher during monsoon and autumn (September and November) which accounted for 80 % of total annual rainfall.

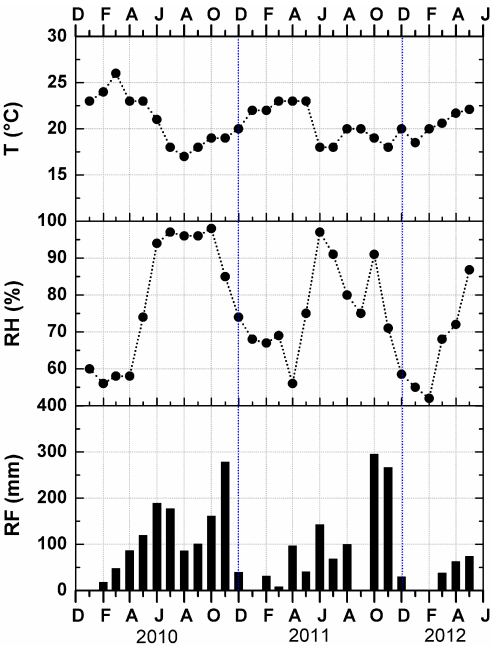

Figure 2. Temporal variation of monthly mean meteorological parameters: temperature (T), relative humidity (RH) and rainfall (RF) at Ooty for the period from January 2010 to May 2012.

The winds however were highly seasonal, with low and moderate (< 4 ms^{-1}) northeasterlies/easterlies dominating the winter (December to February) and summer, changing over to westerlies in monsoon and autumn season as shown by the polar diagram in Fig. 3.

4 Results and discussions

4.1 Temporal variation of BC mass concentration

The regular BC data at 5 min interval over the 2 yr period is examined in Figs. 4 and 5 for the average temporal variations at diurnal and monthly timescales. It is seen that despite the large variation at shorter timescales (Fig. 4), the monthly variation (Fig. 5) has shown a consistent seasonality over the years with a conspicuous peak during summer (when the mean BC is $\sim 0.96 \pm 0.35$ µg m^{-3}) and low in monsoon (with a seasonal mean of 0.23 ± 0.06 µg m^{-3}), an annual amplitude (ratio of max / min) of ∼ 4.

Diurnal variations of BC are very important in understanding the role of mesoscale atmospheric processes and the effect of local human activities. The diurnal variation of the atmospheric boundary layer (ABL) height and its structure is known to influence the surface BC concentrations (Moorthy

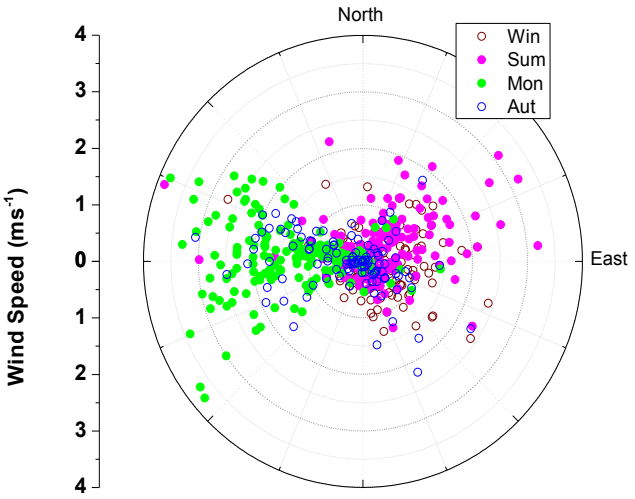

Figure 3. Daily mean values of wind speed and wind direction at Ooty during winter (maroon open circle), summer (pink solid circle), monsoon (green solid circle) and autumn (blue open circle) for the period from April 2010 to May 2012.

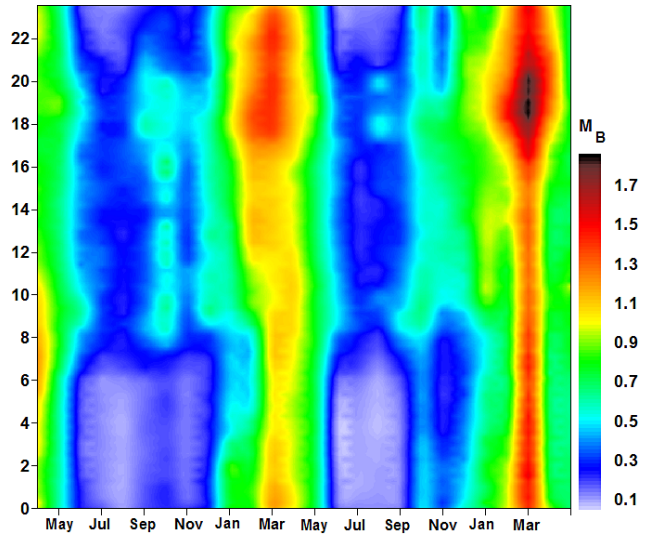

Figure 4. Diurnal variation (local time in hours along the *y* axis) of BC at different months.

et al., 2003; Nair et al., 2007). The present study reveals (Fig. 4) a conspicuous evening peak (during 17:00 to 22:00 local time) in the diurnal variations of BC concentrations at the shorter timescales during February–May, and decrease gradually towards morning and become lowest during the early morning hours (05:00), again increases after the sunrise, typical to a continental site subjected to the dynamics of the atmospheric boundary layer (Nair et al., 2007; Balakrishnaiah et al., 2011). The diurnal variations remain inconspicuous from August to February, even though a less pronounced diurnal pattern similar to that in March–May is noticeable during June and October. Such behaviours suggest an important influence of the strong convective processes in flushing out valley-bound pollutants to the experimental location during summer leading to highest BC concentration. In addition, non-local transport, as well as build-up of aerosols associated with formation of stable layer in the evening might also be playing an important role. Variations of BC with meteorological variables at the site (air temperature, wind speed and direction) during the study period with different ambient conditions are discussed in a following section. With the advent of monsoon, diurnal variation is less pronounced as the much shallower boundary layer isolates the measurement site from the surrounding valley region. All these indicate that the diurnal variation of BC mass concentration at Ooty is similar to those seen over the continents, but at a much subdued strength because of the higher elevation and low thermal gradients of the location during a day.

Despite the large diurnal variation, the annual variation of monthly mean BC mass concentrations (M_{BC}) shown by the box and whisker plot in Fig. 5 depicts a systematic pattern, with the lowest value in July–September and highest during February–April. The solid circles are the monthly means and the whiskers show the standard deviations, while the boxes are used to represent 25 percentile (lower line), median (middle) and 75 percentile (top line) occurrences. The minimum and maximum values for the month are indicated by the open circles. During the study period, the least BC concentration of $0.2 \pm 0.08\,\mu g\,m^{-3}$ occurred in July 2010, while the highest BC abundance of $1.47 \pm 0.16\,\mu g\,m^{-3}$ was found in March 2012. The inter-annual variation of M_{BC} indicates that there is a significant enhancement in BC mass concentrations during March 2012 than those observed for the same period during 2011. The annual mean value of BC estimated from the entire data (irrespective of years) is $0.61 \pm 0.36\,\mu g\,m^{-3}$. In all the above the numbers after the $\pm$ symbol are the standard deviations. The seasonal mean values (in $\mu g\,m^{-3}$) of BC for the measurement period are 0.77 ± 0.20, 0.96 ± 0.35, 0.23 ± 0.06 and 0.35 ± 0.09 respectively for winter, summer, monsoon and autumn, being highest in summer (March to May) and lowest in monsoon.

The frequency distribution of daily mean BC at different seasons (solid line along the left *y* axis in Fig. 6) is highly skewed. During summer, more than 90 % of BC values remain above the annual mean ($0.61 \pm 0.36\,\mu g\,m^{-3}$), while most of the BC values remain below the annual mean during monsoon. The winter months shows a broad distribution of the occurrences of the BC values. The higher BC abundance during the summer is attributed to the increased vertical transport of effluents in the upwind valley regions (as already mentioned), which might have been confined to the surrounding valley regions within the very shallow winter boundary layer. The extended duration of daytime and abundant availability of solar radiation during February–May leads to turbulence and vertical mixing of BC. The local boundary layer influence is also enhanced further by the

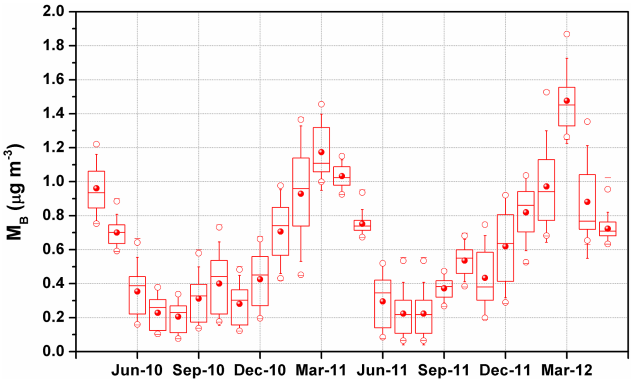

Figure 5. Temporal variations of monthly mean BC. The solid circles are the monthly means and whiskers show the standard deviations. The boxes represent occurrences of 25 percentile (lower line), median (middle) and 75 percentile (top line) BC values.

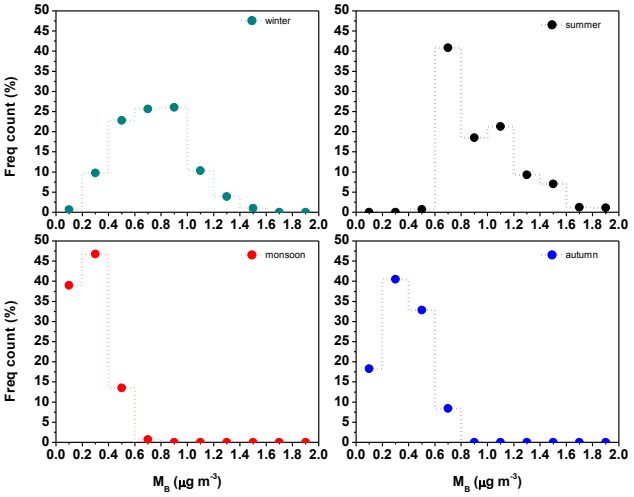

Figure 6. Frequency distribution of BC mass concentrations (M_B) in winter (December–February), summer (March–May), monsoon (June–August) and autumn (September–November) seasons.

long range transported aerosols, contributing to the higher BC concentration in summer. During monsoon, as the temperature decreases to minimum, the convective activity becomes weak, and the ABL shallower. Thus the measurement site (~ 200 m above the surrounding valley region) gets less influenced from the local and regional emissions, which by themselves are meagre. During autumn, the lower replenishment of aerosols after the monsoon washout, as well as the very reduced ABL (due to low solar elevation), lead to a lower value of BC, which gradually increases towards winter mainly due to the increase in local anthropogenic activities in the inhabited areas of Ooty town. With the advent of summer, the increased convection leads again to the deepening, and eventual break-up of the surface layer as the season advances, flushing up particles to be lofted and dispersed spatially by the prevailing winds. This leads to the peak BC concentration at the beginning of summer (e.g. March). However, as monsoon sets in the strong monsoon rain leads to depletion of BC concentration.

4.2 Absorption properties

The estimated monthly mean values of the absorption coefficient (σ_{abs}) at 550 nm varied between the highest value of $\sim 16.37 \pm 4.16\,Mm^{-1}$ in summer and the lowest value $\sim 4.20 \pm 0.99\,Mm^{-1}$ in monsoon. With a view to examining the contribution of distinct aerosol sources in changing the aerosol absorption properties at Ooty, the spectral variations of σ_{abs} are examined, assuming a power law dependence of σ_{abs} with λ of the form

$$\sigma_{abs}(\lambda) = \beta_{abs}\lambda^{-\alpha_{abs}}, \quad (3)$$

where β_{abs} is a constant and α_{abs} represent the absorption (Ångström) exponent. The spectral dependence of aerosol absorption coefficient (σ_{abs}) could be used to identify the presence of aerosol species, other than BC (such as OC and dust) that absorb strongly in the shorter-wavelength (blue

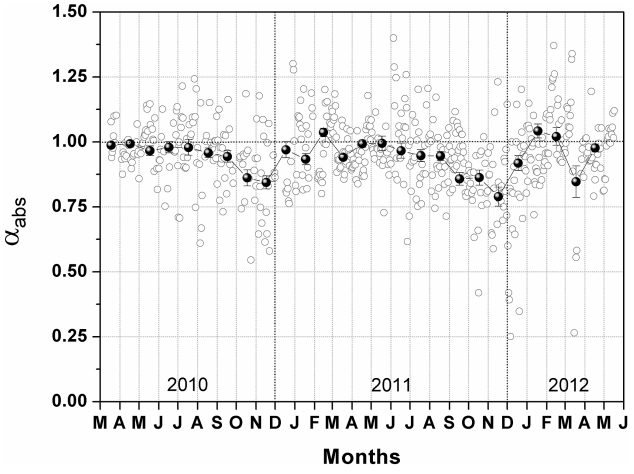

Figure 7. Temporal variation of spectral absorption coefficient (α_{abs}) for daily (open circles) and monthly (solid circles) mean values.

and ultraviolet) spectral regions (Kirchstetter et al., 2004). For BC (elemental) aerosols, originating from fossil fuel combustion, α assumes a value of ~ 1.0 (Kirchstetter et al., 2004). However, if the wavelength dependence of α_{abs} significantly deviates from 1.0, it is indicative of the presence of the absorbing species such as dust or carbonaceous aerosols resulting from biomass burning or brown carbon, the spectral absorption of which increases more rapidly towards lower wavelengths. For example, for biomass smoke and dust aerosols, average values of $\alpha \approx 2$ have been reported (Kirchstetter et al., 2004; Bergstrom et al., 2007).

The monthly variation of α_{abs} superimposed with the daily mean values in Fig. 7 clearly indicates a seasonal change in α_{abs}, with higher values during summer and decreasing

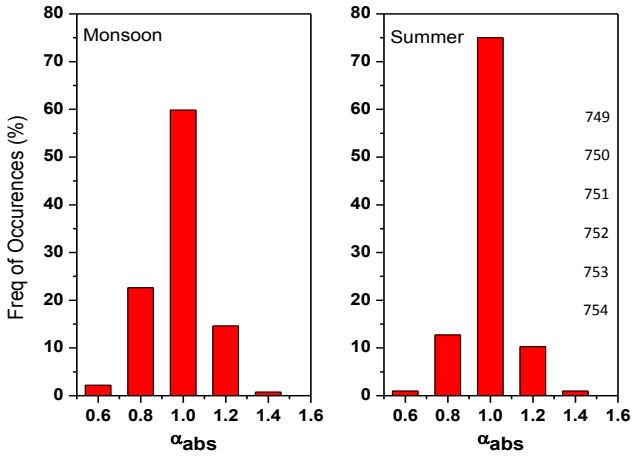

Figure 8. Frequency distribution of the daily mean values of α_{abs} at two representative seasons of monsoon (June–August) and summer (March–May).

afterwards to winter season. However, it is interesting to note that the values of $\alpha_{abs} \sim 1$ in most cases, and > 85 % of the daily mean values remained < 1. This clearly indicates the dominance of fossil fuel aerosols in modifying the aerosol absorption properties at Ooty. On the other hand, the lower values of α_{abs} (< 1.0) during the monsoon season represent the typical background condition of the site with fossil fuel as the only source of spectral aerosol absorption. The frequency distribution of α_{abs}, as shown in Fig. 8 for two typical seasons of summer and monsoon, during which the BC concentration showed highest and lowest BC mass concentrations respectively, also showed no marginal change in the occurrences of the values of α_{abs}.

MODIS fire count

With a view to examining the distribution of potential biomass burning sources surrounding the experimental site and their role in modulating the spectral absorption properties of aerosols at Ooty, MODIS cloud-corrected fire pixels are shown in Fig. 9 for different seasons. The spatial distribution of fires in each season of summer, monsoon, autumn and winter (representing year 2011) in Fig. 9 clearly indicates that total area infested by forest fires and biomass burning is high winter and summer, compared to that during monsoon and autumn. This is well reflected in the monthly variation of α_{abs} (values increasing in winter and summer) in Fig. 7, showing a gradual increase in the relative dominance of biomass burning aerosols during winter and summer. However, wind patterns play a major role in advecting the biomass components, which are discussed below with respect to the local and synoptic conditions around the study region.

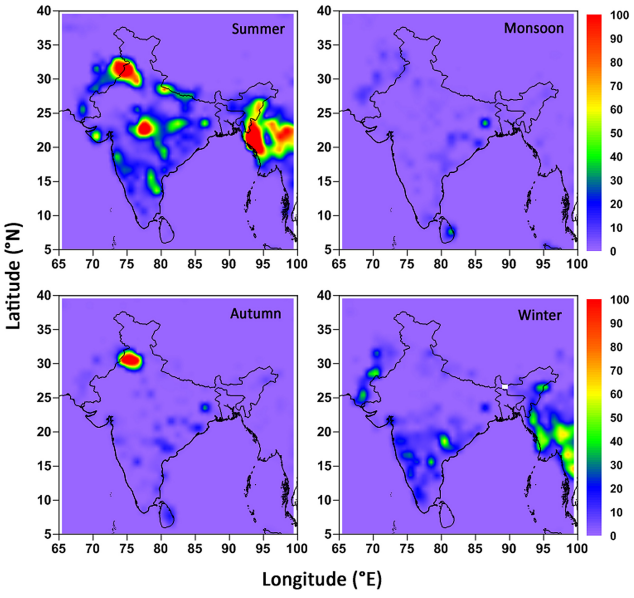

Figure 9. Spatial distribution of cloud-corrected MODIS fire pixel counts over the southern part of India during summer (March–May), monsoon (June–September), autumn (September–November) and winter (December–February) of 2011. Courtesy: Giovanni online visualization and analysis tools.

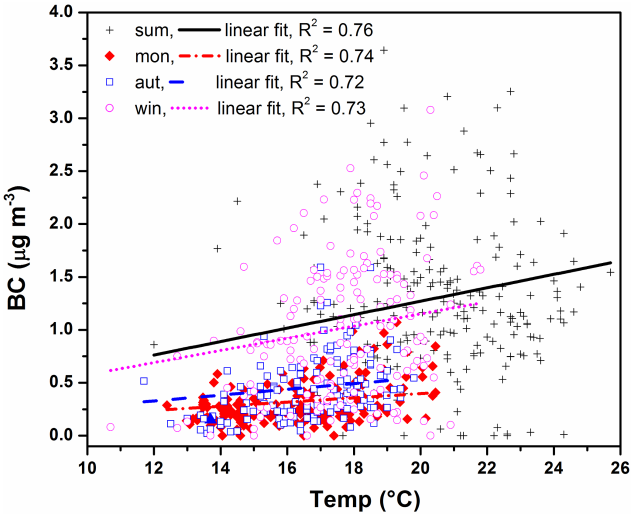

Figure 10. Variation of daily mean values of BC mass concentration with corresponding temperature at different seasons of summer (March–May), monsoon (June–August), autumn (September–November) and winter (December–February).

4.3 Variation of BC with meteorological parameters

To understand the variation of BC with the local ambient conditions at different seasons, the daily mean values of BC are examined first with the variation of daily mean temperature with respect to different seasons as shown in Fig. 10. It can be seen from Fig. 10 that the association and slope

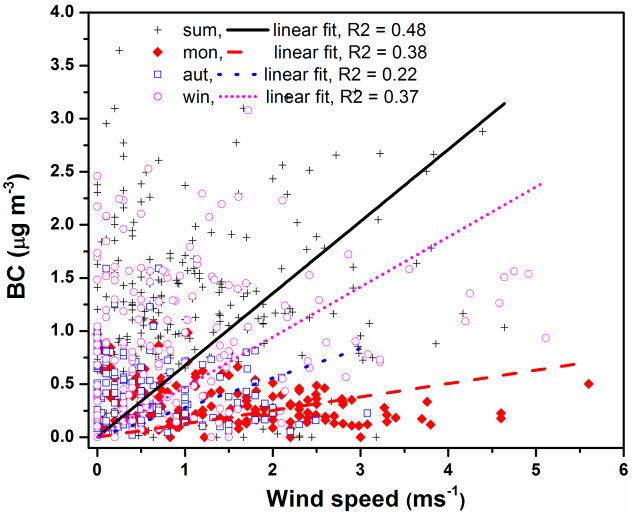

Figure 11. Variation of daily mean values of BC mass concentrations with corresponding wind speed at different seasons of summer (March–May), monsoon (June–August), autumn (September–November) and winter (December–February).

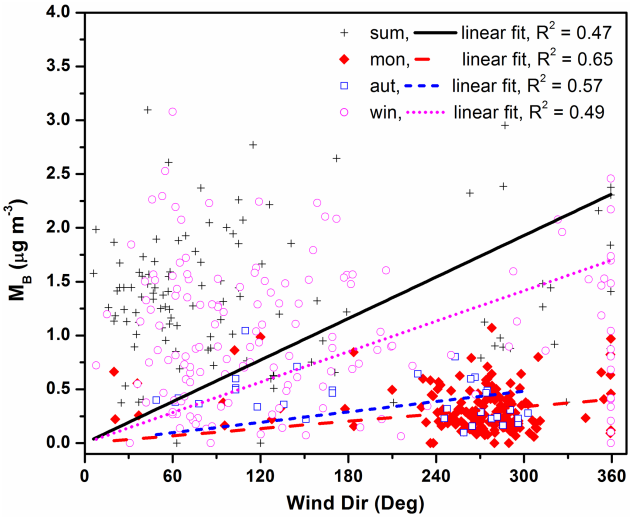

Figure 12. Variation of daily mean values of BC mass concentrations with corresponding wind direction at different seasons of summer (March–May), monsoon (June–August), autumn (September–November) and winter (December–February).

of the variation of BC concentrations with temperatures are higher in summer months in comparison to the other seasons. Since the measurement location is a tourist place, maximum tourists visit Ooty during February to May. In addition, vehicular movement also increases during the peak summer season. Thus, increase in temperature during summer leads to higher dispersion of pollutants from the neighbouring town area and energize particles to reach the measurement site which is at a higher location from the surroundings.

Further, pollutant concentration is also dependent on the strength of the wind. In order to determine the effect of wind on BC concentrations, the variations of daily mean values of BC are examined with the variation of wind speed (Fig. 11) and direction (Fig. 12). Notwithstanding a fair amount of scatter, BC concentrations showed better correlation with increase in wind speed in summer. The increase in wind speed along with ambient temperature causes an increase in the ventilation coefficients, thereby dispersing the aerosols in the ambient air, and consequently causes them to reach the measurement site, which leads to the highest BC concentration during summer. With respect to wind direction in Fig. 12, large changes in BC concentration during summer were associated with northeasterlies and easterlies, when the winds were of continental origin (mainly during summer and winter) from the potential source region of combustion aerosols, while during monsoon, the large reductions in BC concentration were associated with the winds from westerly to northwesterly sectors, i.e. from the marine origin bringing cleaner air to the site.

The above discussion thus indicates the influence of local meteorological parameters (mainly temperature and wind) on the observed high concentration of BC at Ooty during summer seasons.

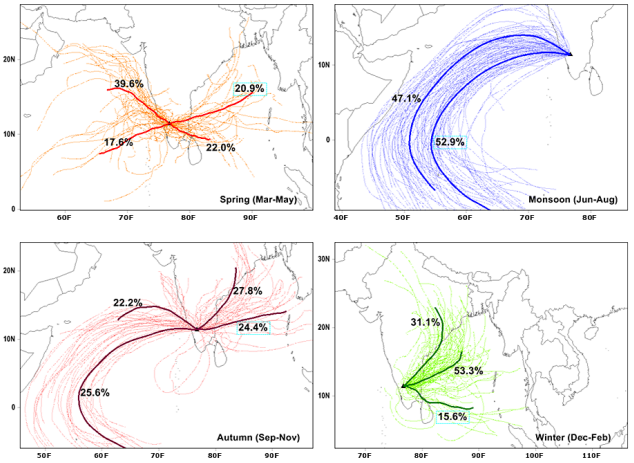

Figure 13. HYSPLIT isentropic back-trajectories for individual days and their cluster mean path during summer (spring), monsoon, autumn and winter seasons. The numbers represent the percentage of trajectories in each cluster.

4.4 Role of long-range transport

With a view to understand the influence of synoptic wind in determining the aerosol absorption characteristics at Ooty, we have examined the 5-day isentropic HYSPLIT back-trajectory (National Oceanic and Atmospheric Administration, NOAA) analysis, ending at 500 m a.g.l. Figure 13 shows the trajectory clusters along with the trajectories for individual days in each season of summer (spring), monsoon, autumn and winter. Consistent with the local meteorological data, the synoptic wind also showed distinct advection pathways with dominant easterly contribution during all seasons,

Table 1. Annual BC mass concentration measured at different locations in India.

Location	Type of location	Altitude (m)	Mean BC ($\mu g\,m^3$)	Reference
High-altitude stations in India				
Nainital (29.40° N 79.5° E)		1958	1.36	Pant et al. (2006)
NCO-P, Nepal (27.95° N 86.82° E)		5079	0.91	Marinoni et al. (2010)
Singhad (18.36° N 73.75° E)		1450	0.86	Raju et al. (2011)
Darjeeling (27.04° N 88.26° E)		2050	5.60	Chatterjee et al. (2010)
Dehradun (30.34° N 78.04° E)		700	4.40	Kant and Dadhwal (2010)
Kullu (31.96° N 77.11° E)		1220	4.60	Raju et al. (2011)
Shillong (25.57° N 91.88° E)		1965	5.00	Kundu and Borgohain (2010)
Hanle (32.78° N 78.95° E)		4520	0.07	Babu et al. (2011a)
Ooty (11.23° N 76.43° E)		2520	0.61	Present Study
Other stations in India				
Anantpur (14.62° N, 77.65° E)	Semi-arid, Rural	331	3.03	Suresh Kumar et al. (2012)
Delhi (28.58° N 77.2° E)	Urban, Industrialized	260	3–27	Beegum et al. (2009)
Pune (18.54° N 73.85° E)	Urban, Industrialized	457	4.1	Safai et al. (2007)
Ahmedabad (23.5° N 72.60° E)	Urban, Industrialized	55	0.21–10.2	Ramachandran and Rajesh (2007)
Hyderabad (17.48° N 78.40° E)	Urban	557	1.5–11.2	Latha et al. (2004)
Bangalore (12.97° N 77.59° E)	Urban, Continental	960	4.2	Babu et al. (2002)
Kanpur (26.47° N 80.33° E)	Urban, Continental	142	6–20	Tripathi et al. (2005)
Trivandrum (8.55° N 76.94° E)	Costal, Urban	10	0.5–8.0	Babu and Moorthy (2002)
Udaipur (24.58° N 73.68° E)	Semi-arid	600	5.6	Vyas (2010)
Bhubaneswar (20.26° N 85.83° E)	Urban	45	5.2	Das (2009)

except in monsoon, where northwesterly marine air mass prevailed. Thus it appears that the potential sources were mainly distributed to the eastern locations of Ooty, i.e. anthropogenically polluted metropolitan cities like Chennai and Bangalore, which mostly modulated the seasonal variation of BC in summer, monsoon and autumn, while the sole marine air mass contribution during monsoon led to the lowest values of BC. Adding to the synoptic source effect, the local thermodynamics in summer support the enhanced concentration of BC at the high-altitude site, leading to the highest concentration at this season.

4.5 Discussion

In Tables 1 and 2, we have compared the observed annual (Table 1) and seasonal (Table 2) mean values of BC at Ooty with those observed at other locations, representative of distinct geographic environments, such as high-altitude, urban, coastal and continental locations.

The annual variation of BC mass concentration at Ooty resembles to those reported for other high-altitude locations. Over the high-altitude Himalayan aerosol observatory at Hanle, Babu et al. (2011b) also reported spring (March–May) high values of BC mass concentrations. Marinoni et al. (2010) also reported maximum BC concentrations ($\sim 340\,ng\,m^{-3}$) at another high-altitude Himalayan site (Nepal Climate Observatory Pyramid) during the pre-monsoon period (April). The seasonal variation of BC concentration at Manora Peak, Nainital also showed maximum values during March to April (Hema et al., 2010–2011). The present study of higher BC loading in summer (March–May) resembles well other high-altitude locations, followed by winter and minimum in the monsoon.

Lee and Kim (2010) reported that over the Southeast Asian region, BC from local emissions accumulates during the boreal spring (March–May). Associated with anthropogenic sources (biomass and fossil fuel burning), the concentration increases at times when local generation of aerosol is prominent. The changes in emission sources and variability in meteorological conditions also play a major role. While the shallower mixed-layer depth and low ventilation coefficient cause higher BC in winter over low-altitude regions, the stronger vertical mixing of aerosol during summer plays a dominant role in the seasonal high concentration of BC at high-altitude locations. On the other hand, a higher rain rate results in a higher aerosol deposition rate of aerosol within a precipitating cloud, while during meagre rainfall, a steady increase in average BC level coupled with continued generation and longer lifetime is expected during dry months over the low-altitude locations. It is seen for our meteorological features in Fig. 2 that 80 % of rainfall occurs during the monsoon season, leading to strong wet removal of aerosols. In comparison to the dry deposition, heavy rainfall resulted in considerably decreased BC concentration, as rainfall is the effective scavenger of atmospheric aerosol.

Table 2. Seasonal variation of BC concentration measured at different locations in India.

Location	Type of location	Measurement method	BC mass concentration ($ng\,m^{-3}$)				References
			Summer	Monsoon	Autumn	Winter	
Bangalore (12.97° N 77.59° E)	Urban, Continental	Aethalometer – Magee Scientific GRIMM optical mass spectrometer	4025	1885	3485	3430	Satheesh et al. (2011)
Hyderabad (17.48° N 78.40° E)	Urban		787	2584	3605	6805	Babu et al. (2011b)
Pune (18.54° N 73.85° E)	Urban, Industrialized	Aethalometer (Magee Scientific AE-42)	3250	1310	6040	7380	Safai et al. (2007)
Delhi (28.58° N 77.2° E)	Urban, Industrialized		12 470	24 870	22 000	12 400	Rai et al. (2002)
Ahmedabad (23.5° N 72.60° E)	Urban, Industrialized		2200	1500	7300	5500	Ganguly and Jayaraman (2006)
Trivandrum (8.55° N 76.94° E)	Coastal, Urban		2620	2010	3460	5680	Krishna Moorthy et al. (2007)
NCOP Nepal (27.95° N 86.82° E)	High altitude	Multi-angle absorption photometer (MAPP-5012 Thermo Electron Corporation)	320	56	137	125	Marinoni et al. (2010)
Hanle (32.78° N 78.95° E)	High altitude	Two-channel aethalometer – (Magee Scientific AE-31)	110	63	72	68	Babu et al. (2011a)
Nainital (29.40° N 79.5° E)	High altitude	Seven-channel aethalometer (Magee Scientific AE-31),	1340	530	1030	1100	Dumka et al. (2010)
Dehradun (30.34° N 78.04° E)	High altitude		4233	2675	3041	6737	Babu et al. (2011b)
Ooty (11.23° N 76.43° E)	High altitude	Seven-channel aethalometer (Magee Scientific AE-31),	960	230	350	770	Present study

5 Conclusions

The continuous measurement of aerosol BC concentrations over the South Indian high-altitude location Ooty for a period of 2 years reveals the distinct nature of the prevalence of absorbing aerosols and their seasonality. On the shorter timescale, the BC concentrations showed prominent diurnal variations during summer (February–May), which were subdued during the other seasons. Seasonally, BC depicted highest mass concentrations (M_{BC}) during summer ($M_B = 0.96 \pm 0.35\,\mu g\,m^{-3}$) and lowest in monsoon ($M_B = 0.23 \pm 0.06\,\mu g\,m^{-3}$). The higher BC abundance during summer is attributed to the increased turbulence and vertical mixing of BC due to extended duration of daytime and abundant availability of solar radiation. In addition, the long-range transported aerosols (dominant easterly advection) also contributed to the higher BC concentration in summer.

Examination of the spectral variation of absorption coefficients at different seasons indicates mainly the dominance of fossil fuel combustion aerosols with highest seasonal mean value of α_{abs} ($\sim 1.24 \pm 0.14$) in summer and lowest α_{abs} ($\sim 0.86 \pm 0.19$) in monsoon. The moderately higher value of α_{abs} in summer thus indicated the presence of biomass burning aerosols too, being influenced by the synoptic winds from the fire infected regions around the experimental site.

The study of the variation of BC with the local meteorological parameters showed better association of the concentration of BC with temperatures during the summer season. The BC concentrations also showed better correlation with wind speed in summer, thus indicating an increase in the ventilation coefficients, which led to the highest BC concentration in summer. The wind of continental origin was found to have significant contribution to higher BC concentration in summer.

The higher BC concentration at higher altitudes during summer (or spring) season has great significance on regional and global climate. It can act as a heat pump over the northern Indian and Himalayan foothill locations and modulate the Indian summer monsoon. Our observation is also in line with earlier observations of the existence of aerosol layers extending from the Indian Ocean to the Himalayan region having a vertical extent of ~ 3 km (Babu et al., 2011a).

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