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Black carbon aerosols over Manora Peak in the Indian Himalayan foothills: implications for climate forcing

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Abstract
This letter presents the contribution of black carbon (BC) to the total aerosol optical depth (AOD) and subsequently to the direct radiative forcing (DRF) at Manora Peak in the Indian Himalayan foothills. Measurements of the chemical composition of aerosols, carried out from July 2006 to May 2007, together with concurrently measured BC mass concentrations were used in an aerosol optical model to deduce the radiatively important aerosol optical parameters for composite aerosols. On the other hand, BC mass concentrations alone were used in the optical model to deduce the optical parameters solely for BC aerosols. The derived aerosol optical parameters were used independently in a radiative transfer model to estimate the DRF separately for composite and BC aerosols. The average BC mass concentration was found to be 0.98 ($\pm$0.68) μg m^{-3} during the entire observation period, which contributes $<$3% to the total aerosol mass and $\sim$17% to the total AOD at Manora Peak. The mean surface forcing was found to be $-$14.0 ($\pm$9.7) and $-$7.4 ($\pm$2.1) W m^{-2}, respectively for composite and BC aerosols whereas mean atmospheric forcing was about +14 ($\pm$10) and +10 ($\pm$3) W m^{-2} for these aerosols. These results suggest that BC aerosols exert relatively large surface heating ($\sim$45% higher) as compared to composite aerosols and contribute $\sim$70% to the total atmospheric forcing at Manora Peak. Such a large warming effect of BC may affect the strength of Himalayan glaciers, monsoon circulation and precipitation over the Indian region.

Keywords: Himalayas, black carbon, aerosol optical depth, radiative forcing

S Online supplementary data available from stacks.iop.org/ERL/7/014002/mmedia

1. Introduction

Atmospheric aerosols, derived from natural as well as anthropogenic emission sources, are known to affect the air quality, human health and radiation budget, and understanding their climatic and environmental effects has been a central theme for the global scientific community. There exists a large spatio-temporal variability and heterogeneity in the abundance pattern of absorbing and scattering particles which, in turn, imparts a large uncertainty in the estimation of radiative forcing as well as assessment of the global climate change due to aerosols (IPCC 2007). In this context, the presence of black carbon (BC) or soot particles, one of the major absorbing and warming components in the lower atmosphere, play a key role in the estimation of optical properties and direct radiative forcing (DRF) on the regional to global scale (Haywood and Shine 1997). The absorbing

nature of BC aerosols leads to an enhanced warming of the atmosphere and atmospheric instability and, consequently, it affects vertical motion, large-scale circulation and the hydrological cycle with significant regional climate effects (Ramanathan *et al* 2001, Meehl *et al* 2008). A recent study suggests that absorbing aerosols, with or without the co-existence of scattering aerosols, have a strong influence on the summer monsoon circulation and the development of convective precipitation over India (Wang *et al* 2009).

BC emission from India constitutes a large fraction of the total global BC burden (Parashar *et al* 2005) and exhibits large spatio-temporal variability in its emission sources (biomass and fossil-fuel) as well as its emission strengths due to varying degrees of land use, transportation and agricultural practices (Gustafsson *et al* 2009, Ram and Sarin 2010, Ram *et al* 2010a). Numerous measurements have been carried out to understand the characteristics of BC aerosols and their contributions to the total aerosol DRF in India at coastal-urban stations (Sreekanth *et al* 2007 and references therein), continental-urban stations (Ramachandran and Kedia 2010 and references therein) and high-altitude stations (Hyvärinen *et al* 2009, Dumka *et al* 2010). Studies at high-altitude sites in the Himalayas are particularly important for understanding their role in radiative forcing and, more importantly, the deposition and melting of Himalayan glaciers, as these sites are also influenced by BC emissions from a variety of source locations (Kopacz *et al* 2011, Kumar *et al* 2011). Furthermore, a considerable amount of BC is associated with the long-range transport (Ram *et al* 2008, Dumka *et al* 2010, Kopacz *et al* 2011) and local emissions from the Gangetic Basin (Ram *et al* 2010a, 2010b, Kumar *et al* 2011) and through mountain breeze circulations (Decesari *et al* 2010) in different parts of the Himalaya. However, studies on BC aerosols and their contribution to the total aerosol DRF over such regions are limited in the literature (Dumka *et al* 2008, Kopacz *et al* 2011).

In the present study, an attempt has been made, for the first time, to assess BC aerosol forcing and its impact at Manora Peak in the Indian Himalayan foothills by utilizing simultaneous measurements of aerosol chemical composition and BC mass concentration over the station. Also, a quantification of the contribution of BC aerosols to the composite aerosol optical depth (AOD) and associated DRF has been investigated in detail.

2. Data and methodology

The station, Manora Peak (29.4°N, 79.5°E), is located at an altitude of ∼2000 m above mean sea level, and is one of the sparsely inhabited Indian stations in the Himalayan foothills (situated ∼100 km south of the main peaks of the Himalaya). The experimental site is situated ∼3 km south of the town of Nainital (a summer resort) and is devoid of any major pollution sources nearby. However, there are small-scale industries located in the valley (like Haldwani, Pantnagar and Rudrapur, ∼30 km to the south of the observational site). Furthermore, the site is under the influence of long-range transport of mineral aerosols from the Middle East and the Thar Desert in western India during the summer months (Hegde *et al* 2007, Srivastava *et al* 2011a).

In order to assess the radiative properties of aerosols, the present study involves simultaneous measurements of chemical composition of composite aerosols and BC mass concentration. Although a total of 19 aerosol samples were collected during July 2006–May 2007, we have used only 14 days data in the present study when simultaneous measurements of chemical composition and BC, along with AOD, are available. The aerosol samples were collected on pre-heated (up to 350 °C) quartz filters (PALLFLEX^{TM}, 2500 QAT-UP, size: 20 × 25 cm^2) using a high-volume sampler (Environtech Ltd, New Delhi, India), operated at a flow rate of 1 m^3 min^{-1}. Each sample was integrated for a time period ranging from 15 to 20 h in order to collect adequate aerosol mass on the filters. The sampled aerosols were analyzed for selected water-soluble inorganic species (SO_4^{2-}, NO_3^-, NH_4^+, Ca^{2+}) along with carbonaceous species (organic and elemental carbon; OC and EC respectively) and water-insoluble OC. The details of the chemical analysis of the aerosols and the meteorological conditions at the station have been discussed in recent publications (Ram *et al* 2008, 2010a, 2010b, Ram and Sarin 2010).

Along with aerosol sampling and chemical composition measurements, BC mass concentrations were measured daily with a temporal resolution of 5 min using a seven-channel Aethalometer (Model AE-42, Magee Scientific, USA). The Aethalometer measures BC mass concentration at seven discrete wavelengths from 0.37 to 0.95 μm. However, the BC mass concentration measured at 0.88 μm wavelength is considered to be representative of BC in the atmosphere as BC is the principal absorber of light at this wavelength while the other aerosol components (e.g. mineral dust) have negligible absorption (Bodhaine 1995). Further details about BC measurement using the Aethalometer are described elsewhere (Dumka *et al* 2010). In addition, measurements of columnar spectral AODs were carried out using a five-channel Microtops II Sun photometer (Solar Light Co., USA) ranging from the ultra violet (0.38 μm) to the near infrared (0.87 μm) spectral regions. AOD measurements, which can only be obtained during the daytime, were recorded every half hour between 09:00 and 16:00. The AOD at a mountain site has a strong diurnal cycle due to the afternoon influx of aerosol-laden air masses (Sagar *et al* 2004). Studies on the diurnal cycle of aerosols over the station clearly show that the concentrations (and probably sources and thus composition) vary greatly over the course of the day, with an inflow from lowlands during the afternoon (Pant *et al* 2006). The AOD measurements were performed only during clear-sky conditions and sufficient care was taken to avoid any manual error such as pointing the photometer toward the Sun. The detailed performance and methodology of the Microtops II Sun photometer is described elsewhere (Srivastava *et al* 2006). For consistency, we have used daily mean AOD values when aerosol sampling was carried out simultaneously.

2.1. Formulation of the aerosol optical model

The AOD, single scattering albedo (SSA) and asymmetric parameter (AP) are the crucial aerosol parameters in the estimation of aerosol DRF. Although direct measurements of SSA and AP were not possible at Manora Peak during the study period, these parameters have been estimated using an aerosol optical model known as optical properties of aerosols and clouds (OPAC), developed by Hess *et al* (1998). The OPAC model provides a wide range of optical and microphysical properties of aerosols and clouds at up to 61 wavelengths between 0.3 μm and 40 μm and for up to eight relative humidity (RH) values. Aerosols in the atmosphere are a mixture of different chemical components (natural and anthropogenic) that can be obtained either through ground-based measurements or by the use of typical mixtures, called aerosol types, given in the OPAC model itself.

In the present study, the daily measured aerosol chemical composition (mainly water-soluble and insoluble) and BC mass concentrations at Manora Peak were used in the OPAC model to estimate various optical properties for composite aerosols. To achieve this, we followed an approach of using available measurements as anchoring points in a standard continental average aerosol type of OPAC model. We fixed the number concentrations of water-soluble, insoluble and BC aerosols on the basis of their measured mass concentrations at the RH closest to the measured ambient RH values. Once the number concentrations of the above components were fixed in OPAC, the number concentrations of the other components, e.g. mineral dust in fine- and coarse-modes, were varied while maintaining the mass fraction of BC, so that the model derived optical properties agreed well with the measured ones. As the OPAC model also estimates the AOD along with the SSA and AP, it can be used to validate the assumed aerosol structure with the measured AOD (from the Microtops II Sun photometer) over the station. The OPAC estimated AOD values were tuned to match the measured AODs by changing number concentrations of various aerosol species in OPAC until they were found to agree within 5% or less (Singh *et al* 2010). A comparison of OPAC estimated AOD values with measured daily mean AODs (at 0.5 μm) during the entire measurement period at Manora Peak is shown in figure 1. The close association between the OPAC estimated AOD and the measured one depicts the near-real scenario of aerosol structure over the experimental site at Manora Peak. Furthermore, to derive the optical properties for the BC aerosols, the measured BC mass concentration was introduced alone as an input into the OPAC model.

Information on the vertical distribution of aerosols over a region is important and one of the sources of uncertainty in the estimation of atmospheric radiative forcing (Lemaître *et al* 2010). However, in the absence of vertical aerosol profiles at Manora Peak, measured surface aerosol properties are attributed to the column properties by making assumptions about the vertical profiles in the OPAC model. Thus, the OPAC estimated aerosol data set of optical properties is assumed to be representative of composite aerosols over Manora Peak. Furthermore, because of the closure with AOD

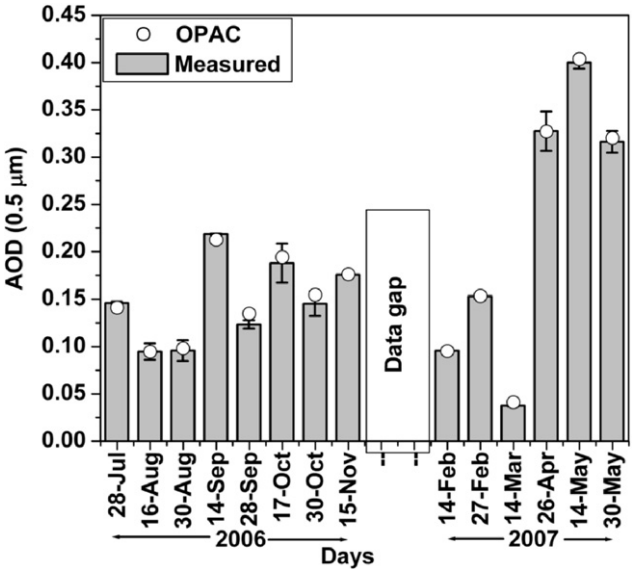

Figure 1. Comparison between the OPAC derived AOD and the measured daily mean AOD at 0.5 μm.

and anchoring of the chemical composition and BC mass fraction, the initial assumptions of the model will not have a significant effect on the estimated radiative forcing (Satheesh and Srinivasan 2006). This method is well established and has been extensively used to derive crucial aerosol optical parameters for radiative forcing estimations at any location (Moorthy *et al* 2005, Pant *et al* 2006, Dey and Tripathi 2008, Singh *et al* 2010, Srivastava *et al* 2011a, 2011b).

2.2. Aerosol DRF estimations

The aerosol radiative forcing at a level in the atmosphere is defined as the change in net global (direct + diffuse) fluxes (down − up) at that level due to aerosols. In this study, the net flux is computed in the shortwave region (0.30–3.0 μm) separately at the top of the atmosphere (TOA) and at the surface with and without aerosols using the Santa Barbara DISORT atmospheric radiative transfer (SBDART) model developed by Ricchiazzi *et al* (1998). The basic input parameters used in the SBDART are spectral AOD, SSA and AP, which were obtained from the OPAC model, as discussed in section 2.1. Besides these, other crucial input parameters include profiles of atmospheric parameters, surface albedo and solar geometry of the location. The profiles of atmospheric parameters (e.g. average temperature, pressure, water vapor and ozone, etc) are generally fixed once the model atmosphere is chosen out of the available options in the SBDART model. The SBDART uses six standard atmospheres to model the vertical profiles. These are defined based on climatic conditions such as tropical, mid-latitude summer, mid-latitude winter, subarctic summer, subarctic winter and US62. These model atmospheres have been widely used in the atmospheric research community and provide standard vertical profiles of temperature, pressure, water vapor and ozone density (Ricchiazzi *et al* 1998). Manora Peak, being located at 29.4°N, falls in the mid-latitudes

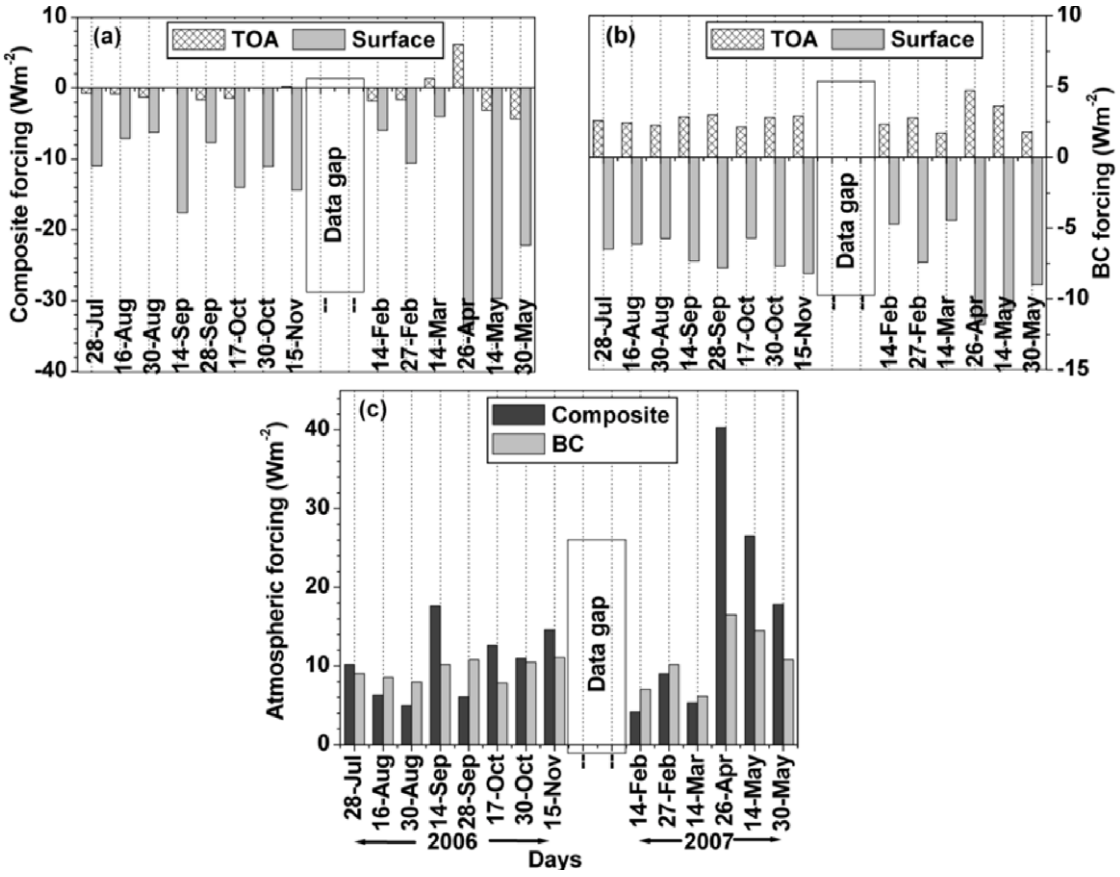

Figure 2. Daily TOA and surface forcing for (a) composite and (b) BC aerosols; (c) resultant atmospheric forcing for composite and BC aerosols.

classification. The mid-latitude summer is characterized by average water vapor of ∼2.9 g cm^{-2} and average total ozone of ∼324 DU, which is close to what is observed over Manora Peak. Thus, we have used the mid-latitude summer climate in the model as it is closest to what is found at Manora Peak. Also, the spectral albedo of the surface over the station was considered as a combination of two basic surface types (sand and vegetation) among the existing surface types in the SBDART model.

Diurnal average aerosol DRF values at the TOA and surface are estimated by computing the differences in the net radiative fluxes (down minus up) with and without aerosols. The difference between the TOA and surface forcing is considered as the atmospheric forcing (ΔF), which represents the amount of energy trapped or absorbed by aerosols within the atmosphere which gets transformed into heat. The heating rate of the atmosphere ($\partial T/\partial t$) due to aerosol absorption is calculated using the following equation:

$$\frac{\partial T}{\partial t} = \frac{g}{C_p}\frac{\Delta F}{\Delta P} \tag{1}$$

where g is the acceleration due to gravity, C_p is the specific heat capacity of air at constant pressure, ΔF is the resultant atmospheric forcing and ΔP is the atmospheric pressure difference between the top and bottom boundaries of each layer.

3. Results

The mean concentration of total suspended particulate (TSP) mass (±standard deviation) over the station was observed to be ∼41 (±16) μg m^{-3} during the entire observation period, and found to vary from 23 μg m^{-3} (on 28 July 2006; monsoon) to 83 μg m^{-3} (on 28 September 2006; post-monsoon). The corresponding mean BC mass concentration was 0.98 (±0.68) μg m^{-3} (range: 0.13–2.12 μg m^{-3}) and the AOD (at 0.5 μm) was 0.18 (±0.10) (range: 0.14–0.40) at Manora Peak. It is quite discernible that BC contributes only 2.4% to the total aerosol mass (i.e. TSP, which contains mostly coarse-mode particles) during the entire observation period at Manora Peak. BC aerosols are mainly associated with fine-mode particles and, in spite of this small BC mass fraction, their contribution to the total AOD (0.5 μm) was found to be high (∼17%).

The daily values of TOA and surface radiative forcing estimated for composite aerosols are shown in figure 2(a). Negative surface forcing, the net flux received at the surface after passing through the atmosphere, implies a net cooling effect. However, positive TOA forcing, on a few days, indicates a net warming effect, which mainly arises due to highly reflecting continental surface albedo and/or strong aerosol absorption (Pandithurai *et al* 2008). Composite aerosol forcing at the surface was observed to be well correlated with the observed composite AODs. Relatively

higher surface forcing was observed on some days in summer (26 April 2007, 14 May 2007 and 30 May 2007), and was attributed to the observed high values of AOD over the station during these days (figures 1 and 2(a)). The mean surface and TOA forcing values were found to be −14.0 (±9.7) and −0.7 (±2.4) W m^{-2}, respectively, for composite aerosols when averaged over the entire period.

Similarly, figure 2(b) shows daily values of TOA and surface forcing, estimated solely for BC aerosols over the station. By and large, a similar pattern with relatively lower magnitude of surface forcing was observed for BC aerosols as compared to those for composite aerosols during the entire period. In contrast to composite aerosols, the TOA forcing for BC aerosols was found to be positive for all the days. The mean BC forcing values were found to be −7.4 (±2.1) and +2.7 (±0.8) W m^{-2}, respectively, at the surface and TOA when averaged over the entire period. Relatively large surface heating (less negative) was observed due to BC (∼45% higher) as compared to the composite aerosols, which was more pronounced during the summer (∼63% higher), and has raised several climatic issues in the Himalayan region (Lau *et al* 2010).

The resultant positive atmospheric forcing (implying a warming effect) due to composite and BC aerosols is shown in figure 2(c). The positive atmospheric forcing can directly intensify the low-level inversion, which slows down the surface convection and in turn inhibits cloud formation (Sreekanth *et al* 2007). The composite aerosol forcing was found to be higher than the BC forcing mostly during the summer and post-monsoon days, and was more pronounced during the summer. However, the opposite was observed on some days in the monsoon (16 August 2006, 30 August 2006 and 28 September 2006), and on all the days in winter (14 February 2007, 27 February 2007 and 14 March 2007). A relatively large magnitude of atmospheric forcing, for both composite and BC aerosols, was observed during the summer as compared to the other days with a large positive difference. The results could be associated with the enhanced dust loading (transported from the desert regions), which leads to an increase in the magnitude of AOD (Hegde *et al* 2007, Srivastava *et al* 2011a), along with enhanced BC aerosols from biomass burning (a potential BC source) emissions from the southwest regions (Kumar *et al* 2011). In this study, the magnitude of the AOD and the mass concentration of BC were observed to be relatively higher during the summer periods (mean AOD = 0.35 ± 0.05 and mean BC = 1.55 ± 0.63 μg m^{-3}) than on other days. On the other hand, a relatively low magnitude of atmospheric forcing for composite and BC aerosols was observed in the winter (except in the monsoon) and the results are associated with a low magnitude of AOD (0.09 ± 0.06) and BC (1.02 ± 0.81 μg m^{-3}). Due to the high elevation of the station, the study site is mostly above the boundary layer where the temperature drops to a very low level and the thermal convection is weak (Pant *et al* 2006). As such, the site is well above the convective boundary layer, which results very low AOD values during the winter (Sagar *et al* 2004, Pant *et al* 2006).

Apart from the total aerosol burden (in terms of AOD) in the atmosphere, the magnitude of atmospheric forcing is also highly associated with the nature and mixing of aerosols. For example, mineral dust mixed with BC exerts a large heating on the atmosphere due to the absorbing nature of both the aerosols, which is the probable case observed in the present study during the days in summer. Mixing of mineral dust with the other aerosol species during transportation has been found to affect the overall optical and radiative properties of aerosols (Mishra *et al* 2008). On the other hand, emissions of absorbing BC aerosols that are co-emitted with scattering aerosols (e.g. sulfate and organic carbon) result in lower radiative forcing than BC alone (Ramana *et al* 2010), which is the probable case observed in the present study during the days in winter.

The mean atmospheric forcing, averaged over the entire period, over the station is about +14 (±10) W m^{-2} for composite aerosols (which translates into a heating rate of 0.4 K day^{-1}) and +10 (±3) W m^{-2} for BC aerosols (which translates into a heating rate of 0.3 K day^{-1}). The results suggest that the overall contribution of BC to the total atmospheric forcing over the station is ∼70%. In earlier studies, Sreekanth *et al* (2007) have reported an ∼65% contribution of BC to composite aerosol forcing at a coastal-urban station (Visakhapatnam) whereas Panicker *et al* (2010) have reported relatively less (∼55%) contribution at a continental-urban station (Pune). The remaining ∼30% of the total atmospheric forcing (in the present study) may be attributed to the other natural absorbing species such as mineral dust. Dust aerosols mainly originate from convectively activated surface soil and transportation from the desert regions of south Asia, and are predominant during the summer (Hegde *et al* 2007, Ram *et al* 2008, Srivastava *et al* 2011a).

As far as the uncertainty in estimations of various aerosol optical parameters in the OPAC model is concerned, it mainly arises from the uncertainty in the estimation of the composition of aerosol types, the state of mixing assumptions and the vertical distribution of aerosols in the atmosphere (Singh *et al* 2010). Although it is not possible to ascertain the exact uncertainty due to these factors in this study, we have performed a sensitivity analysis for the effect of BC mass concentration on various aerosol parameters. In order to do this, the OPAC model was run several times with the BC mass concentration varying from 0.2 to 2.2 μg m^{-3} with an increment of 0.2 μg m^{-3}, keeping all other parameters constant. The derived optical parameters such as AOD, SSA and AP at 0.5 μm wavelength for different BC mass concentrations are shown in supplementary figure S1 (available at stacks.iop.org/ERL/7/014002/mmedia). It is noticed that an increase in the BC concentration from 0.2 to 2.2 μg m^{-3} leads to a decrease in the SSA from 0.91 to 0.85 and a corresponding increase in the AOD from 0.39 to 0.41. However, no significant change was observed in the AP with increasing BC mass concentrations.

Further, to understand the effect of BC mass concentration on aerosol radiative forcing, the retrieved optical parameters for different BC mass concentrations were used

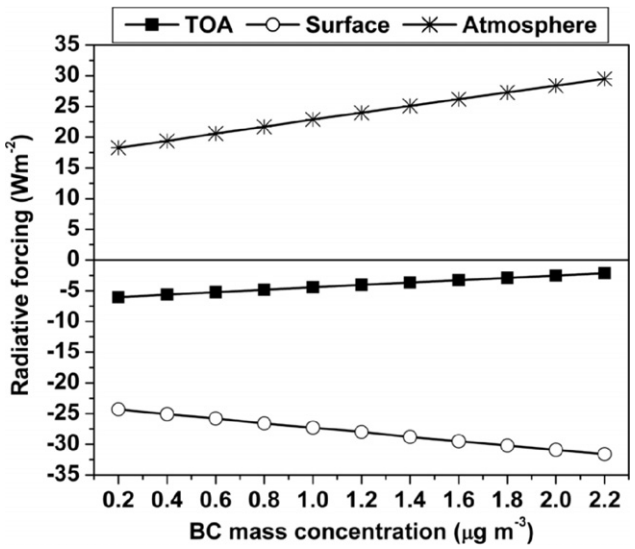

Figure 3. The effect of change in the BC mass concentration on the radiative forcing values at the TOA, surface and atmosphere.

in the SBDART model to estimate aerosol DRF values at the TOA, surface and in the atmosphere (figure 3). The results clearly suggest that due to the enhancement in BC aerosols, forcing at the TOA leads to a greater warming effect while it leads to a greater cooling effect at the surface. However, the resultant atmospheric forcing leads to more warming in the atmosphere and consequently to more atmospheric heating. Thus we can see that on an average in the range of simulation (i.e. 0.2–2.2 μm^{-3} BC mass concentration), an increase of 0.2 $\mu g\ m^{-3}$ in BC mass concentration over the station changes the TOA forcing by 0.4 W m^{-2} (toward more warming) and the surface forcing by 0.7 W m^{-2} (toward more cooling). As a result, the resultant atmospheric forcing changes by 1.1 W m^{-2} (toward more warming), which consequently can change the atmospheric heating rate by 0.03 K day^{-1}.

4. Discussion and conclusions

Earlier studies have reported on measurements of aerosol optical and chemical characteristics over Manora Peak (Sagar *et al* 2004, Srivastava *et al* 2006, Dumka *et al* 2010, Ram *et al* 2010a). In addition, Pant *et al* (2006) have reported wintertime (December) aerosol characteristics and their implications for shortwave radiative forcing over the station. In the absence of measured aerosol chemical characteristics, they retrieved aerosol optical parameters (essential for radiative forcing estimations) by assuming different aerosol types in the OPAC model. However, knowledge of the chemical composition of the aerosol is essential for an accurate assessment of aerosol radiative forcing, which provides a near-real-time scenario for the aerosol DRE over the region. In the present study, we have utilized real-time aerosol chemical data measured at Manora Peak from July 2006 to May 2007 to retrieve crucial aerosol optical parameters from OPAC and also to understand their implications for the climate system.

The OPAC derived aerosol optical properties, independently for composite and BC aerosols, were incorporated in the SBDART model to derive the radiative forcing over Manora Peak. The average BC mass concentration over the station was found to be 0.98 ($\pm$0.68) $\mu g\ m^{-3}$ during the entire observation period, which contributes $\sim$2.4% to the total aerosol mass measured over the station. The results suggest that, in spite of this small BC mass fraction (as they are fine-size aerosols) over Manora Peak, the average contribution was high ($\sim$17%) in the total AOD (at 0.5 μm). The mean surface forcing, averaged during the entire period, was found to be -14.0 ($\pm$9.7) W m^{-2} for composite aerosols and -7.4 ($\pm$2.1) W m^{-2} for BC aerosols. The results suggest that BC aerosols exert relatively large surface heating ($\sim$45% higher) as compared to the composite aerosols in the Himalayan region, which may have an implication for snow melting through deposition onto snow surfaces and via dynamical coupling between land and atmosphere (Lau *et al* 2010). Furthermore, the mean atmospheric forcing values were found to be about $+14$ ($\pm$10) and $+10$ ($\pm$3) W m^{-2}, respectively, for composite and BC aerosols. As a result, BC was found to contribute $\sim$70% to the total atmospheric forcing, which consequently can alter the tropospheric temperature and cloud formation processes.

Although the composite aerosol forcing estimated at Manora Peak is relatively lower as compared to other locations (Kaufman *et al* 2002, Ramanathan and Ramana 2005, Dey and Tripathi 2008, Srivastava *et al* 2011b), it was found to be relatively higher as compared to the value reported by Pant *et al* (2006) during the winter period. However, the magnitude of radiative forcing was found to be similar to those reported by Srivastava *et al* (2011a) at Manora Peak during the summer. In another study, Ramana *et al* (2004) have reported relatively large atmospheric forcing of $+25$ W m^{-2} over the Himalayan region. On the contrary, BC aerosol forcing was found to be relatively lower as compared to other locations (Sreekanth *et al* 2007, Panicker *et al* 2010). Studies at various high-altitude sites in the Himalayas (Flanner *et al* 2007, Ming *et al* 2008, Marcq *et al* 2010, Kopacz *et al* 2011) have reported the mean BC aerosol forcing to be in the range of $+0.4$ to $+3.5$ W m^{-2} during clear-sky conditions and $+3.8$ to $+15.6$ W m^{-2} due to changes in snow albedo induced by the deposition of BC (Kopacz *et al* 2011). Also, Flanner *et al* (2007) have estimated up to $+20$ W m^{-2} radiative forcing due to the BC induced snow albedo effect in the Tibetan plateau during the spring whereas Ming *et al* (2008) have reported $+4.5$ W m^{-2} in the eastern Himalayas during the summer.

Due to the general circulation patterns, the Himalayan region is a strong receptor of aerosols from far-off regions of major emission sources in India/Pakistan and parts of China (Marcq *et al* 2010, Kopacz *et al* 2011). Furthermore, the region is also influenced by the long-range transport of mineral dust aerosols from the Thar Desert regions, predominantly during the summer (Hegde *et al* 2007, Ram *et al* 2008, Srivastava *et al* 2011a). In addition, to the north and northeast of the observing site there is the sharply undulating topography of the Himalayan mountain ranges; however, to the southwest of the site there is low elevated plain land

merging into the highly polluted regions of the Indo-Gangetic Basin (IGB). Aerosols over the IGB region are highly associated with the emissions from various anthropogenic and natural sources, and are thus identified as being comprised of different types (Srivastava *et al* 2011c), which build up due to the high population density and unique topography of the region. Due to the combined effects of the IGB topography and the Himalayan orography, these aerosols are lifted up quite often to the high-altitude regions (Marcq *et al* 2010, Srivastava *et al* 2011a). Absorbing aerosols in the elevated regions heat the mid-troposphere by absorbing solar radiation, and produce an atmospheric dynamical feedback called the elevated heat pump (EHP) effect. Consequently, this can lead to an increase in the summer monsoon rainfall over India (Lau *et al* 2006) and enhancement in the rate of snow melting in the Himalayan regions (Lau *et al* 2010).

The transport of optically active materials to the climatically sensitive regions of the Himalayas is, therefore, a key issue in understanding the impact of absorbing BC aerosols on the Indian summer monsoon region and, in particular, on the precipitation pattern over the Himalayan regions as well as on frozen water storage (Marcq *et al* 2010). In fact, an increase in the concentration of BC in this region not only affects the energy budget of the atmosphere, but also modifies the energy budget of snow surfaces by deposition, which leads to a decrease in snow albedo (Flanner *et al* 2009, Yasunari *et al* 2010). This in turn can accelerate the melting of the Himalayan glaciers and, thus, affect the water resources for millions of people in the Ganges downstream region (Lau *et al* 2010, Yasunari *et al* 2010). The crucial issue of the impact of optically active particulate materials (mainly BC aerosols) on the local energy budget in the Himalayan regions has been put forward in the present study. Such studies raise several climate related issues, which need to be addressed on the basis of long-period investigations in the Himalayan regions to improve our scientific understanding of the regional climate on the inter-annual as well as intra-seasonal scale.

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