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 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 (±0.68) µg m−3 during the entire observation period, which contributes <3% to the total aerosol mass and ∼17% to the total AOD at Manora Peak. The mean surface forcing was found to be −14.0 (±9.7) and −7.4 (±2.1) W m−2, respectively for composite and BC aerosols whereas mean atmospheric forcing was about +14 (±10) and +10 (±3) W m−2 for these aerosols. These results suggest that BC aerosols exert relatively large surface heating (∼45% higher) as compared to composite aerosols and contribute ∼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

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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 spatial-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™, 2500 QAT-UP, size: 20 × 25 cm²) using a high-volume sampler (EnvironTech Ltd, New Delhi, India), operated at a flow rate of 1 m³ 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 (SO₄²⁻, NO₃⁻, NH₄⁺, Ca²⁺) 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.

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 (Lemaitre 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 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 (Moorby 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.

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 $-14.0 \pm 9.7$ and $-0.7 \pm 2.4$ 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 $-7.4 \pm 2.1$ and $+2.7 \pm 0.8$ 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 ($\sim$45% higher) as compared to the composite aerosols, which was more pronounced during the summer ($\sim$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 $\pm$ 0.05 and mean BC = 1.55 $\pm$ 0.63 $\mu$g 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 $\pm$ 0.06) and BC (1.02 $\pm$ 0.81 $\mu$g 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 $+14 \pm 10$ W m$^{-2}$ for composite aerosols (which translates into a heating rate of 0.4 K day$^{-1}$) and $+10 \pm 3$ 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 $\sim$70%. In earlier studies, Sreekanth et al (2007) have reported an $\sim$65% contribution of BC to composite aerosol forcing at a coastal-urban station (Visakhapatnam) whereas Panicker et al (2010) have reported relatively less ($\sim$55%) contribution at a continental-urban station (Pune). The remaining $\sim$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 $\mu$g m$^{-3}$ with an increment of 0.2 $\mu$g m$^{-3}$, keeping all other parameters constant. The derived optical parameters such as AOD, SSA and AP at 0.5 $\mu$m 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 $\mu$g 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.
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 µg m⁻³ BC mass concentration), an increase of 0.2 µg 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 (±0.68) µg m⁻³ during the entire observation period, which contributes ∼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 (∼17%) in the total AOD (at 0.5 µm). The mean surface forcing, averaged during the entire period, was found to be −14.0 (±9.7) W m⁻² for composite aerosols and −7.4 (±2.1) W m⁻² for BC aerosols. The results suggest that BC aerosols exert relatively large surface heating (∼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 (±10) and +10 (±3) W m⁻², respectively, for composite and BC aerosols. As a result, BC was found to contribute ∼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). 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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References

Bodhaine B A 1995 Aerosol absorption measurements at Barrow, Mauna Loa and the South Pole J. Geophys. Res. 100 8967–75

Deccarsi S et al. 2010 Chemical composition of PM$_{2.5}$ and PM$_{1}$ at the high-altitude Himalayan station Nepal Climate Observatory-Pyramid (NCO-P) (S079m a.s.l.) Atmos. Chem. Phys. 10 4583–96

Dey S and Tripathi S N 2008 Aerosol direct radiative effects over Kanpur in the Indo-Gangetic basin, northern India: long-term (2001–2005) observations and implications to regional climate J. Geophys. Res. 113 D04212

Dumka U C, Moorothy K K, Kumar R, Hegde P, Sagar R, Pant P, Singh N and Babu S S 2010 Characteristics of aerosol black carbon mass concentration over a high altitude location in the Central Himalayas from multi-year measurements Atmos. Res. 510–21

Dumka U C, Moorothy K K, Satheesh S K, Sagar R and Pant P 2008 Short period modulations in aerosol optical depths over central Himalaya: role of mesoscale processes J. Appl. Meteorol. Clim. 47 1467–75

Flanner M G, Zender C S, Hess P G, Mahowald N M, Painter T H, Ramanathan V and Rasch P J 2009 Springtime warming and reduced snow cover from carbonaceous particles Atmos. Chem. Phys. 9 2481–97

Flanner M G, Zender C S, Randerson J T and Rasch P J 2007 Present-day climate forcing and response from black carbon in snow J. Geophys. Res. 112 D111202

Gustafsson Ö, Kruså M, Zencak Z, Sheesley R J, Granat L, Engström E, Praveen P S, Rao P S P, Leck C and Rodhe H 2009 Brown clouds over South Asia: Biomass or fossil fuel combustion Science 323 495–8

Haywood J M and Shine K P 1997 The effect of anthropogenic sulfate and soot aerosol on the clear sky planetary radiation budget Geophys. Res. Lett. 24 603–6

Hegde P, Pant P, Naja M, Dumka U C and Sagar R 2007 South Asian dust episode in June 2006: aerosol observations in the central Himalayas Geophys. Res. Lett. 34 L23802

Hess M, Koepke P and Schultz I 1998 Optical properties of aerosols and clouds: the software package OPAC Bull. Am. Meteorol. Soc. 79 831–44

Hyvärinen A-P, Lihavainen H, Koppula M, Sharma V P, Kerminen V-M, Panwar T S and Visanen Y 2009 Continuous measurements of optical properties of atmospheric aerosols in Mukteshwar, northern India J. Geophys. Res. 114 D08207

IPCC 2007 Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge: Cambridge University Press) chapter 2, p 129

Kauffman Y J, Tanre D and Boucher O 2002 A satellite view of aerosols in the climate system Nature 419 215–23

Kopacz M, Mauzerall D L, Wang J, Leibensperger E M, Henze D K and Singh K 2011 Origin and radiative forcing of black carbon transported to the Himalayas and Tibetan Plateau Atmos. Chem. Phys. 11 2837–52

Kumar R et al. 2011 First ground based observations of influences of springtime Northern Indian biomass burning over the central Himalayas J. Geophys. Res. 116 D19302

Lau K M, Kim M K and Kim K M 2006 Asian summer monsoon anomalies induced by aerosol direct forcing: the role of the Tibetan Plateau Clim. Dyn. 26 65–64

Lau K M, Kim M K, Kim K M and Lee W S 2010 Enhanced surface warming and accelerated snow melt in the Himalayas and Tibetan Plateau induced by absorbing aerosols Environ. Res. Lett. 5 052024

Lemaître C, Flamant C, Cuesta J, Raut J-C, Chazette P, Formenti P and Pelon J 2010 Radiative heating rates profiles associated with a springtime case of Bodélé and Sudan dust transport over West Africa Atmos. Chem. Phys. 10 8131–50

Marcq S et al. 2010 Aerosol optical properties and radiative forcing in the high Himalaya based on measurements at the Nepal Climate Observatory-Pyramid site (S079m a.s.l.) Atmos. Chem. Phys. 10 5859–72

Meghla G A, Arbaster J M and Collins W D 2008 Effects of black carbon aerosols on the Indian monsoon J. Clim. 21 2869–82

Mehra S K, Dey S and Tripathi S N 2008 Implications of particle composition and shape to dust radiative effect: a case study from the Great Indian Desert Geophys. Res. Lett. 35 L23814

Ming J, Cacher H, Xiao C, Qin D, Kang S, Hou S and Xu J 2008 Black carbon record based on a shallow Himalayan ice core and its climatic implications Atmos. Chem. Phys. 8 1343–52
Moorthy K K, Babu S S and Satheesh S K 2005 Aerosol characteristics and radiative impacts over the Arabian Sea during the inter-monsoon season: results from ARMEX Field campaign J. Atmos. Sci. 62 192–206

Pandithurai G et al 2008 Aerosol radiative forcing during dust events over New Delhi, India J. Geophys. Res. 113 D13209

Panicker A S, Pandithurai G, Safai P D, Dipu S and Lee D-I 2010 On the contribution of black carbon to the composite aerosol radiative forcing over an urban environment Atmos. Environ. 44 3066–70

Pant P et al 2006 Aerosol characteristics at a high-altitude location in central Himalayas: optical properties and radiative forcing J. Geophys. Res. 111 D17206

Parashar D C, Gadi R, Mandal T K and Mitra A P 2005 Carbonaceous aerosol emissions from India Atmos. Environ. 39 7861–71

Ram K and Sarin M M 2010 Spatio-temporal variability in atmospheric abundances of EC, OC and WSOC over northern India J. Aerosol Sci. 41 88–98

Ram K, Sarin M M and Hegde P 2008 Atmospheric abundances of primary and secondary carbonaceous species at two high-altitude sites in India: sources and temporal variability Atmos. Environ. 42 6785–96

Ram K, Sarin M M and Hegde P 2010a Long-term record of aerosol optical properties and chemical composition from a high-altitude site (Manora Peak) in Central Himalaya Atmos. Chem. Phys. 10 11791–803

Ram K, Sarin M M and Tripathi S N 2010b A 1 year record of carbonaceous aerosols from an urban site in the Indo-Gangetic Plain: characterization, sources, and temporal variability J. Geophys. Res. 115 D24313

Ramachandran S and Kedia S 2010 Black carbon aerosols over an urban region: radiative forcing and climate impact J. Geophys. Res. 115 D10202

Rama M V, Ramanathan V, Feng Y, Yoon S-C, Kim S-W, Carmichael G R and Schauer J J 2010 Warming influenced by the ratio of black carbon to sulphate and the black carbon source Nature Geosci. 3 542–5

Ramana M V, Ramanathan V, Podgorny I A, Pradhan B B and Shrestha B 2004 The direct observations of large aerosol radiative forcing in the Himalayan region Geophys. Res. Lett. 31 L05111

Ramanathan V, Crutzen P J, Kiehl J T and Rosenfeld D 2001 Aerosols, climate, and the hydrological cycle Science 294 2119–24

Ramanathan V and and Ramana M V 2005 Persistent, widespread, and strongly absorbing haze over the Himalayan foothills and the Indo-Gangetic plains Pure Appl. Geophys. 162 1609–26

Ricchiai Z, Yang S, Gautier C and Sowle D 1998 SBDART: a research and teaching software tool for plane-parallel radiative transfer in the earth’s atmosphere Bull. Am. Meteorol. Soc. 79 2101–14

Sagar R, Kumar B, Dumka U C, Moorthy K K and Pant P 2004 Characteristics of aerosol spectral optical depths over Manora Peak: a high altitude station in the central Himalayas J. Geophys. Res. 109 D06207

Satheesh S K and Srinivasan J 2006 A method to estimate aerosol radiative forcing from spectral optical depths J. Atmos. Sci. 63 1082–92

Singh S, Soni K, Bano T, Tanwar R S, Nath S and Arya B C 2010 Clear-sky direct aerosol radiative forcing variations over mega-city Delhi Ann. Geophys. 28 1157–66

Sreekanth V, Niranjan K and Madhavan B L 2007 Radiative forcing of black carbon over eastern India Geophys. Res. Lett. 34 L17818

Srivastava A K, Pant P, Hegde P, Singh S, Dumka U C, Naja M, Singh N and Bhavanikumar Y 2011a Influence of south Asian dust storm on aerosol radiative forcing at a high-altitude station in central Himalayas Int. J. Remote Sens. 32 7827–45

Srivastava A K, Singh S, Tiwari S and Bish S D 2011b Contribution of anthropogenic aerosols in direct radiative forcing and atmospheric heating rate over Delhi in the Indo-Gangetic Basin Environ. Sci. Pollut. Res. at press (doi:10.1007/s11356-011-0633-y)

Srivastava A K, Tripathi S N, Dey S and Kanawade V P 2011c Inferring aerosol types over the Indo-Gangetic Basin from ground based sunphotometer measurements Atmos. Res. under review

Srivastava M K, Singh S, Saha A, Dumka U C, Hegde P, Singh R and Pant P 2006 Direct solar ultraviolet irradiance over Nainital, India, in the central Himalayas for clear-sky day conditions during December 2004 J. Geophys. Res. 111 D08201

Wang C, Kim D, Ekman A M L, Barth M C and Rasch P J 2009 Impact of anthropogenic aerosols on Indian summer monsoon Geophys. Res. Lett. 36 L21704

Yasunari T J et al 2010 Estimated impact of black carbon deposition during pre-monsoon season from Nepal Climate Observatory-Pyramid data and snow albedo changes over Himalayan glaciers Atmos. Chem. Phys. 10 6603–15