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Impact of Black Carbon and Other Aerosols on Himalayan Glaciers: A Brief Review

Alok Sagar Gautam[1] and H.C. Nainwal[2]*

[1]Department of Physics, H.N.B. Garhwal University, Srinagar Garhwal, Uttarakhand, India
[2]Department of Geology, H.N.B. Garhwal University, Srinagar Garhwal, Uttarakhand, India
✉ nainwal61@gmail.com

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Abstract: Black carbon aerosol plays a unique and important role in Earth's climate system to rise the average global surface temperature, thus responsible for warming the globe. Black carbon (BC) is a type of carbonaceous material with a unique combination of physical properties. These assessments provide an evaluation of black-carbon climate forcing that is comprehensive in its inclusion of all known and relevant processes and that is quantitative in providing best estimates and uncertainties of the main forcing terms: direct solar absorption, ice clouds and accumulation of snow/ice over the Himalayan glaciers. Any changes in the total radiative forcing would lead to drastic changes in the impact of BC aerosols over the glaciers and affect downstream flows of melt water streams emanating from glaciers as well as micro-climatic condition of the terrain.

Keywords: Black carbon; Aerosols; Himalayas; Glacier; Climate.

Introduction

Aerosols enhance the back scattering of solar radiation and lead to negative radiative forcing while the absorbed Black Carbon (BC) aerosols lead to the positive effect. Aerosol, the optically absorbing part of the carbonaceous aerosols, is the major anthropogenic component of the atmospheric aerosol system. It is one of the important constituents of ambient particulate matter, which is emitted into the atmosphere as a by-product of combustion processes such as fossil fuels, forest fire, industrial effluent etc. The increase in anthropogenic emission would increase in aerosol loading, thereby reducing the incoming solar radiation reaching to the ground surface. These effects influence regional aerosol radiative forcing (Nair et al., 2013; Haywood and Shine, 1997). Studies at high altitude sites in the Himalayas are particularly important to understand their role in radiative forcing and, more importantly, the melting of Himalayan glaciers, as these sites are also influenced by BC emissions from a variety of source locations (Kopacz et al., 2011; Bond et al., 2013).

Concentration of BC vary in the clean environments of the Antarctica, and high altitude regions. However, observations of higher concentrations of Aitken particles during the high Sun periods suggest generation of nucleation mode particles by photochemical reactions and thermodynamical processes. Low surface area provided by the aerosols at high altitude regions and the presence of high concentration of sulphate and di-methyl sulphide (DMS) at high altitude regions in Himalaya are proposed as possible source for generation of such ion/particles/BC aerosols during High Sun periods. One of the possible sources of BC in Himalayan region may be transportation of polluted material through wind from Indo Gangetic Plain (IGP).

*Corresponding Author

National and International Status

Among the various aerosol types, BC aerosols are known for their potential to agitate the Earth Radiative Balance of Earth-Atmosphere system and thus forcing the regional climate in numerous pathways (Lau et al., 2006; IPCC, 2007; Flanner et al., 2009; UNEP, 2011) leading to complex responses in the Earth-Climate (Hansen et al., 2005; Shindell et al., 2010). In addition to the direct radiative interaction with solar and terrestrial radiation via scattering and absorption, BC aerosols modify the cloud's micro-physical properties (indirect and semi-direct effect) and reduce the albedo of the snow due to deposition of BC over the glaciers (Flanner et al., 2007; IPCC, 2007).

The radiative forcing due to direct, semi-direct and snow-albedo effects of BC aerosols and their implications on the hydro-climate are amongst the major challenges in the regional climate impact assessments (Flanner et al., 2007; Nigam and Bollasina, 2010). Deposition of absorbing aerosols (mainly BC and dust) on highly reflecting surfaces (like snow or ice) would reduce the surface albedo significantly and result in positive radiative forcing (warming) at the top of the atmosphere (TOA) (Hansen and Nazarenko, 2004; Jacobson, 2001; Painter et al., 2007). The global mean radiative forcing due to BC-induced snow darkening is estimated as $+0.1\pm0.1 W\ m^{-2}$, which offsets ~20% of the cooling due to aerosols at the TOA (IPCC, 2007). Hansen et al. (2005) have shown that snow-albedo modification via BC deposition has very high efficacy of climate forcing compared to direct and semi-direct BC forcing and that for most of the other climate forcing agents. Even though several studies have addressed the radiative impacts of BC on snow, quantitative estimates of radiative forcing have been made recently. Measurements of BC on snow have been reported from several locations on the Tibetan plateau and southeastern Himalayas (Ming et al., 2012, 2009; Xu et al., 2009; Huang et al., 2011) and reflect their significant contribution in the glacier retreat.

In the backdrop of all of the above, continuous measurements of aerosols including BC have been initiated at high-altitude stations as well as lower Himalayan stations under the Aerosol Radiative Forcing over India (ARFI) project of ISRO-Geosphere Biosphere Programme (IGBP). These observations revealed different processes responsible for the short and long range transportation of atmospheric aerosols to the Indian continent including Himalayan region. Ming et al. (2009) revealed that deposition of BC in the snow surface might intense the melting of glaciers in west China and reduced albedo were over 5% due to deposition of BC.

The changes in climate variability have led to a rapid retreat of mountain glacier systems which may adversely affect the lifeline of river basins and ecosystems. Most of the Himalayan glaciers are retreating and BC Aerosol/Aerosol may be one of the causes of their retreat. Nainwal et al. (2016) reported that during the period of 1936-2013, the Satopanth and Bhagirath Kharak glaciers located at the head of Alaknanda valley, Chamoli district are retreating at the rates of 9.7 m/a and 7.0 m/a respectively. During the past several decades, the other glaciers located in the Uttarakhand Himalaya are also retreating. The Gangotri glacier has retreated at an average rate of about 19 m/a during 1935-1999 (Srivastava, 2004). Snout retreat rates of Chorabari glacier during 1962-2012 (Dobhal et al., 2013) and Dokiriani glacier during 1962-2007 (Dobhal and Mehta, 2010) have been reported to be 6.8 m/a and 15 m/a respectively. Between the period of 1963-1989, Dobhal et al. (1995) estimated 7.5 m/year retreat of Chhota Shigri glacier located in Himachal Pradesh. But a recent study carried out by Kulkarni et al. (2007) reported an accelerated retreat of 32 m/yr during 1988 to 2003. A highly negative mass balance was observed in the Chhota Shigri glacier from 2002 to 2006 (Wagnon et al., 2007).

In Central Himalaya, India since the mid 1970s the average air temperature measured at 49 stations shows the raise by 1°C, with high elevation sites warming the most. This is twice as fast as the 0.6°C average warming for the mid latitudinal Northern Hemisphere (20° to 40°N) over the same time period, and illustrates the high sensitivity of mountain regions to climate change (ICIMOD, 2002; Shrestha et al., 1999). As Himalayan glaciers are retreating, glacial lakes are swelling up which may lead to catastrophic flooding in downstream areas. Apart from these studies, 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.

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), continental-urban stations (Ramachandran and Kedia, 2010) and high-altitude stations (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 retreat of Himalayan glaciers may be influenced by BC emissions from a variety of source locations (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) and local emissions from the Gangetic plain (Ram et al., 2010, Kumar et al., 2011) and through mountain breeze circulations in different parts of the Himalaya. However, studies on BC aerosols and their contribution to the total aerosol direct radiative forcing (DRF) over such regions is limited in the literature (Dumka et al., 2010).

UNEP (2011) report reveals that Black carbon (BC, Box 1) and tropospheric ozone (O_3, Box 2) are harmful air pollutants that also contribute to climate change. Here, Box 1 refereed as Black carbon (BC) exists as particles in the atmosphere and is a major component of soot. BC is not a greenhouse gas. Instead it warms the atmosphere by intercepting sunlight and absorbing it. BC and other particles are emitted from many common sources, such as cars and trucks, residential stoves, forest fires and some industrial facilities. BC particles have a strong warming effect in the atmosphere, darken snow when they are deposited, and influence cloud formation. Other particles may have a cooling effect in the atmosphere and all particles influence clouds. In addition to having an impact on climate, anthropogenic particles are also known to have a negative impact on human health.

Similarly, Box 2 refereed as Ozone (O_3) is a reactive gas that exists in two layers of the atmosphere: the stratosphere (the upper layer) and the troposphere (ground level to ~10–15 km). In the stratosphere, O_3 is considered to be beneficial as it protects life on Earth from the sun's harmful ultraviolet (UV) radiation. In contrast, at ground level, it is an air pollutant harmful to human health and ecosystems, and it is a major component of urban smog. In the troposphere, O_3 is also a significant greenhouse gas. The threefold increase of the O_3 concentration in the northern hemisphere during the past 100 years has made it the third most important contributor to the human enhancement of the global greenhouse effect, after CO_2 and CH_4. In recent years, scientific understanding of how BC and O_3 affect climate and public health has significantly improved. This has catalysed a demand for information and action from governments, civil society and other stakeholders. The United Nations (UN) has been requested to urgently provide science based advice on action to reduce the impacts of these pollutants.

So far no systematic work is carried out regarding the BC on the glaciers of western Himalaya. Some minor attempts on BC were carried out on the Parvati Glacier (Himachal Pradesh), glaciers of Bapsa Basin (Himachal Pradesh) etc. There is a need to start a systematic work focused on the BC/Aerosols so that we can understand the rate of deposition of black carbon in the glaciers that reduce the albedo of snow thus leading to faster melting of glaciers and causing greater negative impacts on the ecosystem of the area. Keeping views in mind, in this paper, we summarize here the importance of the black carbon aerosol study and its relationship with various meteorological parameters and assessment of the impact of BC and other aerosol on the retreat of Himalayan glaciers. This review paper provides an insight of the evolution of BC and its characteristics over Himalayan glacier. Dynamics of the boundary layer state of the atmosphere over the Himalayan glacier is explained with help of statistical analysis of diurnal, seasonal and annual variations of the BC aerosol. The assessment of the direct and indirect BC aerosol climate forcing over Himalayan region of Uttarakhand is also explained.

Sources and Sink of BC Aerosol

Natural and anthropogenic emissions sources are for BC aerosol. The natural emission source includes volcanic eruption, forest fires etc. The anthropogenic sources mainly consists the combustion of coal, oil and other fossil fuels, biomass burning and transportation exhaust emission. BC aerosol is a strong absorbent of solar radiation, which induces a net warming in the earth-atmosphere system. BC mainly originates from the partial combustion of fossil fuel and biomass. Other major BC sources include vehicular exhausts, industrial activities, crop residue burning and long-range transport. Black carbon (BC) emissions from India for the year 2011 are estimated to be 901.11 ± 151.56 Gg yr^{-1} based on a new ground-up, GIS-based inventory (Paliwal et al., 2016). On a global basis, approximately 20% of black carbon is emitted from burning biofuels, 40% from fossil fuels, and 40% from open biomass burning (Ramanathan and Carmichael, 2008). A more detailed study reports (a) 42% Open biomass burning (forest and savanna burning), (b) 18% Residential biofuel burned with traditional technologies, (c) 14% Diesel engines for transportation, (d) 10% Diesel engines for industrial use, (e) 10% Industrial processes and power generation, usually from smaller boilers and (f) 6% Residential

coal burned with traditional technologies. BC sources vary by region. Some investigators have argued that fossil fuel and biofuel black carbon have significantly greater amounts of black carbon than scattering, making reductions of these sources particularly powerful mitigation strategies. However, this may not hold good for the Indian region because of large Organic Carbon to Black Carbon ratios observed from measurements. Thus, extensive measurements and modelling studies need to be carried out before we can formulate black carbon reduction strategies. Recently, brown carbon (humic-like substance) resulting from biomass burning has attracted global attention because of its significantly differing absorption properties, compared to BC. Brown carbon absorbs strongly at blue and UV region, with very little absorption in the mid-visible (Ramanathan and Carmichael, 2008).

Diurnal, Seasonal and Annual Variation of BC Aerosol

Day-to-day fluctuation in the BC aerosols is very much important to understand the physics of mesoscale process in the atmosphere. It is well known that diurnal variation of Boundary layer and its structure influence the surface boundary concentrations (Nair et al., 2007; Udayasoorian et al.; Guha et al., 2015). 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 (Nair et al., 2007). Studies suggest an important influence of the strong convective processes leading to highest BC concentration.

Role of BC Aerosol in Radiative Transfer in the Atmosphere

BC aerosol particles play a large role in the transfer of solar radiation in the troposphere. The radiative effect of two major BC aerosols components viz., organic aerosol and BC has gained much more attention. The radiative effect of BC are more complex and involves various type of interactions with other aerosol constituents. In this paper, we have explained about one dimensional radiative transfer model for the calculation of direct radiative forcing which is developed by Charlson et al. (1992) and further modified by Chylek and Wong (1995). From this model, an equation was derived from the radiative transfer equations assuming, optical thin layer ($T_{sc} << 1$) and non-absorbing aerosol particles. This equation expresses the forcing due to the change in the reflectance of the earth-atmosphere system.

Aerosol forcing ΔF_R is expressed as

$$\Delta F_R = -(S_0/4)\, T^2_{atm}\, (1-N)\, (1-\alpha)^2 2\beta\, T_{sc} \qquad (1)$$

where S_0 is the solar constant, T^2_{atm} is the transmittance of the atmosphere above the aerosol layer, N is the cloud fraction cover, α is the albedo of the underlying surface, β is the fraction of the radiation scattered upward, τ_{sc} is the scattering optical thickness of the aerosol layer. β equals to 0.5 for small size of the particle.

In the expression $S_0/4$ represents the globally averaged incident solar flux at the top of the atmosphere, T^2_{atm} reduces the incident and reflected flux by the transmittance of the atmosphere above the aerosol layer, N is the fractional cloud cover, in line with the assumption that the aerosol is significant only in cloud-free areas. Boucher and Anderson (1995) pointed out that this assumption is not correct, since aerosol forcing under cloudy sky is about 25% as efficient.

Chylek and Wong (1995) modified this term to account for the effect of absorbing aerosols

$$\Delta F_R = -(S_0/4)\, T^2_{atm}\, (1-N)\, [\, (1-\alpha)^2 2\beta\, T_{sc} - 4\alpha T_{abs}] \qquad (2)$$

where T_{abs} is the absorption optical thickness of the aerosol layer. For the conservative case of purely scattering aerosol i.e. when $\tau_{abs} = 0$, the formula reduces to equation (1). It was shown that large error can be introduced into the calculation of the top of the atmosphere (TOA) direct forcing when the aerosol with a single scattering albedo of 0.97 is assumed to be purely scattering ($\omega_0 = 1$). Another method of the estimation of Radiative Forcing is explained by Panicker et al. (2010). Measurements of aerosol chemical composition is used to estimate the aerosol radiative forcing. Radiative forcing estimated due to presence of BC aerosols alone by neglecting other aerosol components as the exact forcing is also affected by how the BC aerosols are mixed with other aerosol constituents (Jacobson, 2001). In order to describe the implications of BC aerosols alone over the radiative forcing, the measured BC values are used as an input parameter to the optical properties of aerosol and cloud (OPAC) model given by Hess et al. (1998). Thus the important optical parameters such as aerosol optical depth (AOD), single scattering albedo (SSA) and asymmetry parameter are estimated at different wavelengths in short wave (SW) region. For this, he followed an approach given by Moorthy et al. (2005) by using measured BC mass

concentration alone as anchoring points in a standard continental average aerosol model while neglecting the other types of aerosol in the model, which is then fine-tuned to match the measurements. The measured BC is used to represent as soot particles in the model. BC aerosol optical parameters are deduced from the OPAC model and fed into the Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART) model given by Ricchiazzi et al. (1998) for BC aerosol forcing estimations. The difference between the TOA and surface forcing is considered as atmospheric forcing (ΔF), which represents the amount of energy trapped or absorbed by the aerosols within the atmosphere and gets transformed into heat.

Direct BC radiative forcing (RF) is defined as the difference in net fluxes at the surface, bottom of atmosphere (BOA), or at the top of atmosphere (TOA), with and without BC. The RF is given by the expression:

$$(\mathrm{RF})_{\mathrm{BOA,\ TOA}} = [F_{\mathrm{BC}} - F_{\mathrm{No\ BC}}]_{\mathrm{BOA,\ TOA}} \quad (3)$$

where

$$F_{\mathrm{BC,\ No\ BC}} = (F\downarrow - F\uparrow)_{\mathrm{BC,\ No\ BC}} \quad (4)$$

The difference between the radiative forcing at the top of the atmosphere and the surface is designated as the atmospheric forcing and is written as

$$(\mathrm{RF})_{\mathrm{ATM}} = (\mathrm{RF})_{\mathrm{TOA}} - (\mathrm{RF})_{\mathrm{BOA}} \quad (5)$$

where the subscript ATM represents the energy trapped within the atmosphere due to the presence of black carbon. If the $(\mathrm{RF})_{\mathrm{ATM}}$ is positive, the BC produces a net gain of radiative flux leading to heating, while a negative $(\mathrm{RF})_{\mathrm{ATM}}$ indicates a net loss and thereby cooling.

Role of BC Aerosol in Indirect Radiative Forcing

Aerosol indirect effect is a suite of complex processes by which aerosol perturb the earth-atmosphere radiation balance by modulation of cloud albedo and cloud amount (Penner et al., 2001). Aerosol indirect effect on climate is defined as the changes in radiation due to modification of cloud microphysics by aerosols acting as cloud condensation nuclei (CCN). There are two such major indirect effects. While one predicts an increase in cloud albedo due to an increase in the number of aerosols for a fixed liquid water path (LWP) (Twomey,1977), the other one predicts an increase in cloud lifetime due to the reduced size of cloud effective radius caused by more aerosols (Albrecht, 1989; Manoj et al., 2012; Jung et al., 2013). The schematic of these processes linking aerosol mass, cloud condensation nuclei (CCN) and ice nuclei (IN) concentrations to cloud physical properties and effect is shown in Figure 1. The aerosol indirect effect is usually divided into two basic categories. The first indirect effect or Twomey effects related to the increased aerosol and CCN number concentration that decreases the effective cloud radius and consequently to the increased mean cloud droplet number concentration and resulting increase in cloud reflectivity for marine stratus clouds (Twomey et al., 1977).

The second indirect effect, which is also linked to the decrease of the effective cloud droplet radius, is associated with the suppression of precipitation and resulting increase in fractional cloudiness. Although these terms refer primarily to warm clouds, there have been observational as well as theoretical indications that cirrus clouds may also be affected by aviation-related aerosol (Fahey et al., 1999). The upward trend in cirrus fractional cloudiness in areas of high air traffic over the last two decades beyond the extent attributable to linear contrails alone was considered as evidence for the perturbation caused by anthropogenic aerosol. BC in and around the cloud absorbs solar radiation and evaporates the liquid water content, resulting in dissipation of clouds, known as the semi-direct effect (Koch and Del Genio, 2010). The indirect forcing exerted by BC is a little-explored area. The aerosol indirect forcing is a quantitative measure of changes in radiation due to relative changes in aerosol-cloud microphysical parameters. Most of the studies in this area are model-based and very few studies report observation-based estimates (McComiskey and Feingold, 2008). The Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX) was carried out over northeast (NE) India to study the characteristics of aerosols and clouds in a highly polluted environmental condition and to investigate how the cloud micro-physics is altered under such conditions. Panicker et al. (2014) have found indications of the semi-direct effect induced by BC over the region.

Black Carbon and Other Aerosols over the Glaciers: Its Relationship with Meteorological Parameters

Oerlemans (2001) described about the role of meteorological parameters at glaciers. He showed that at Samaden which is known as Sankt Moritz airport,

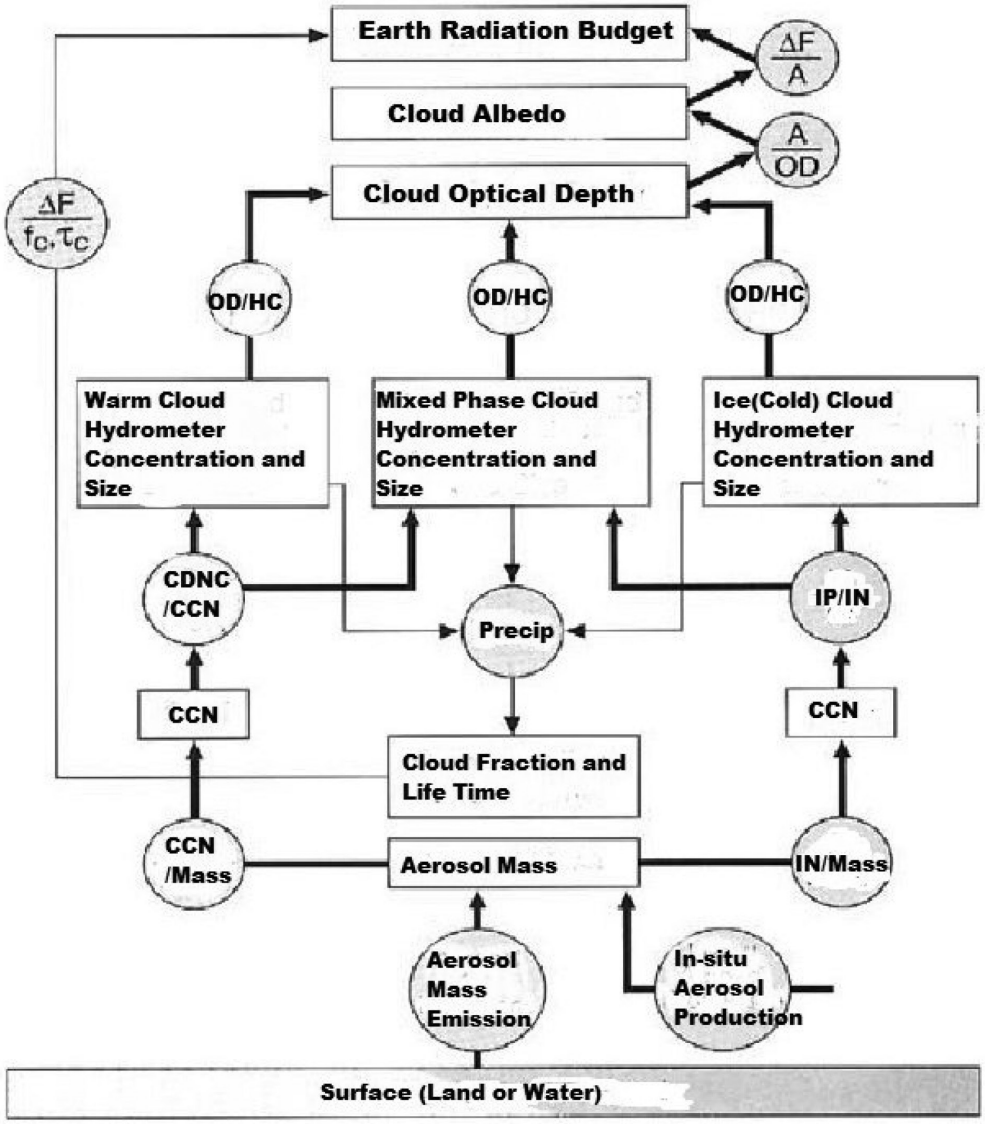

Figure 1. The schematic of processes linking aerosol mass, cloud condensation nuclei (CCN) and ice nuclei (IN) concentrations to cloud physical properties and effect (Penner et al., 2001).

wide valley of 12 km from Moteratschgletsher, the temperature range is 20K and wind speed closely follows air temperature through the day. The minimum wind speed lags behind maximum temperatures by a few hours (Figure 2). The enhancement of higher BC concentration over the glaciers govern nature of the atmospheric boundary layer (ABL) and the wind speed (ws), which is dependent on the season. The ABL also becomes highly stable in nature during the winter season due to low surface convection. This does not allow aerosol particles to disperse much into the atmosphere and it gets trapped within the boundary layer near to the surface, as observed at Delhi (Srivastava et al., 2012). Apart from the prevailing meteorological conditions, the potential sources of burning such as wood, waste and coal in and around the station are also responsible for the increased BC concentration over the station during the winter period (Khillare et al., 2004).

The concentration of soot also increases because of the transport of pollutants from thermal power plants by prevailing north westerlies over Delhi (Bano et al., 2011). On the other hand, Manora Peak, being a high altitude station, is mostly above the boundary layer during the winter when the temperature drops to a very low level and the thermal convection is weak (Pant et al., 2006), resulting in very low BC values. On the other hand, an increase in the vertical extent of ABL occurs because of strong convection during the summer,

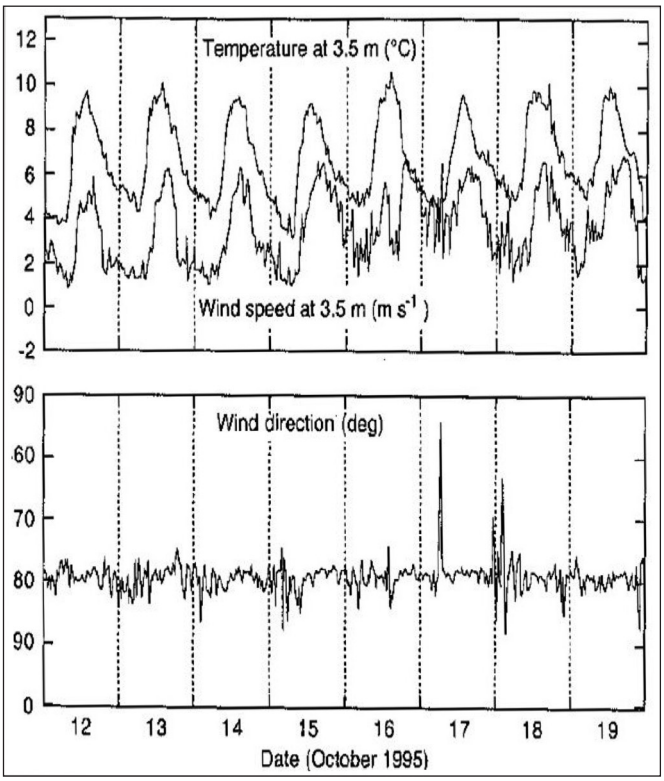

Figure 2. Glacier wind as measured on the tongue of the Morteratschgletsher for a fair weather period in autumn. A wind direction of 1800 corresponds to downslope flow (Oerlemans, 2001, Glacier and Climate change, GBP2405 O47, ISBN 9026518137).

which tends to disperse the particulate matters upto the higher altitudes and reduce surface level aerosol concentrations (Srivastava et al., 2012). However, the observed high BC at Manora Peak during the spring may largely be associated with the long-range transport of the emissions from the Ganga basin (Kumar et al., 2011). The impact of biomass burning over the northern Indian Subcontinent are studied in the central Himalayan region using three years (2007–2009) data from surface and space-borne observations along with a radiative transfer model. Analysis of high confidence MODIS fire counts data show that fire activity over the northern Indian Subcontinent is highest during spring and the majority of the fires in this region are associated with crop residue burning. These northern Indian fires are shown to substantially impact the regional atmospheric composition (Kumar et al., 2011).

Yang et al. (2016) depict that during the summer of 2013 and 2014, the Laohugou glacier No. 12 (LHG, 39°10′ - 35′ N, 96°10′ - 35′ E, located at Qilian Mountains, northeastern margin of the Tibetan Plateau-TP) showed a much lower Black Carbon (BC) and Mineral Dust (MD) concentrations in snow than ice and gradually declined with increasing elevation. The effects of BC and MD on albedo reduction at different melting conditions were identified with the Snow/Ice Aerosol Radiative (SNICAR) model initiated by in-situ observation data. The sensitivity analysis showed that BC had a stronger impact on albedo reduction than MD on this glacier. The impacts of BC represented around 45% of albedo reduction while the contribution of MD was 35% when the glacier surface was presented as superimposed ice and experienced intensive melting. During summer, when the surface was covered by snow, BC and MD contributed for 15% and 9% respectively. On an average, the radiative forcing (RF) caused by BC in the snow/ice, more than MD, was 41.6 ± 37.0 Wm^{-2}. Meanwhile, compared to glacier melting in summer of 2013 and 2014 (409 mm w.e. and 366 mm w.e., respectively) calculated using the surface energy-mass balance model, contributions of BC and MD were less than 37% and 32% respectively of summer melting, while MD and BC together contributed a maximum of 61%. This study provides the baseline information on BC and MD concentrations in glaciers of the northeastern TP and their contributions in glacier melting during summer (Yang et al., 2016).

Conclusion

In the recent years, many researchers have proposed the BC emission to be included in the greenhouse gases inventory. Paliwal et al. (2016) have explained the BC emission inventory in detailed way. The uncertainties in net climate forcing from black-carbon-rich sources are substantial, largely due to lack of knowledge about cloud interactions with both black carbon and co-emitted organic carbon. In prioritizing potential black-carbon mitigation actions, non-science factors such as technical feasibility, costs, policy design and implementation feasibility play important roles. The major sources of black carbon are presently in different stages with regard to the feasibility for near-term mitigation. This assessment by evaluating the large number and complexity of the associated physical and radiative processes in black-carbon climate forcing, sets a baseline from which to improve future climate forcing estimates (Bond et al., 2013).

BC aerosols play a complex and important role in the climate effect of the atmospheric aerosol. Thus, research on global and regional scale is very much important and possesses positive implications in protecting the atmospheric environment and human health. Short life

time of BC aerosol is able to reduce global warming by controlling BC emission. There is a need to carry out spatial and temporal observations for a long time period on BC aerosol. The thrust areas of research may be improvement of source emission data and analysis, study of chemical reactions on the aerosol and their mixing states with other aerosols, impact of BC aerosols on the melting of glaciers and related climate feedback and the indirect effect of BC aerosol on climate.

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