Aerosol Radiative Forcing Estimation over a Remote High-altitude Location (~4900 masl) near Yala Glacier, Nepal

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ABSTRACT

In the present study, we estimated the aerosol radiative forcing and heating rates near Yala Glacier, Nepal (28.21°N, 85.61°E; 4900 masl), using in situ black carbon (BC) mass concentration measurements, satellite data sets, and model simulations. The real-time ambient BC mass concentration was continuously measured using an Aethalometer (AE-33) from October 2016 to May 2017. The Optical Properties of Aerosols and Clouds (OPAC) model was used to simulate the aerosol optical properties in conjunction with the in situ measurements and satellite data sets. Outputs from OPAC and the satellite data sets were used as inputs for the Santa Barbara Discrete Ordinate Radiative Transfer Atmospheric Radiative Transfer (SBDART) model to estimate the radiative forcing. The in situ measurements showed that the BC mass concentration peaked during the pre-monsoon season ($707.9 \pm 541.8 \text{ ng m}^{-3}$), which was corroborated by the higher aerosol optical depth (AOD) values during this season (0.058 ± 0.002). The diurnal cycle of the BC mass concentration exhibited a night-time low and afternoon high, which were influenced by the boundary layer dynamics and valley wind flow pattern. The Concentration Weighted Trajectory (CWT) analysis indicated diverse source regions, including northern Asia, the Indo-Gangetic Plain (IGP), and parts of Nepal and Bangladesh. The Moderate Resolution Imaging Spectroradiometer (MODIS)-derived AOD and Ångström exponent (AE), and the OPAC-simulated single-scattering albedo (SSA) and asymmetry parameter (AP) over the study site were estimated to be 0.048 ± 0.009 and 1.32 ± 0.01 , and 0.938 ± 0.019 and 0.710 ± 0.042 , respectively, during the study period. The mean radiative forcing during the study period for the top of the atmosphere, surface and atmosphere were 3.4, -0.5 and 3.9 W m^{-2} , respectively. Higher atmospheric forcing was observed in the pre-monsoon season, leading to changes in the heating rates.

Keywords: Black carbon; Heating rates; Himalayas; OPAC; SBDART.

INTRODUCTION

Atmospheric aerosols are tiny particles suspended in the earth's atmosphere. Directly, aerosols absorb and scatter the incoming solar and the outgoing terrestrial radiation, thereby affecting the earth's energy budget. Indirectly, aerosols affect the cloud microphysics, altering the cloud albedo through their role as cloud condensation nuclei. Upon deposition on snow or ice, aerosols reduce the surface albedo significantly, resulting in positive radiative forcing (Twomey, 1977; Charlson and Schwartz, 1992; Gul *et al.*, 2018). This effect of aerosols on warming or cooling of the atmosphere is

expressed in terms of aerosol radiative forcing, or ARF (Haywood *et al.*, 1999). Amidst other aerosols, black carbon (BC) particles are light absorbing and an important short-lived climate forcing agent (Twomey, 1977; Liou, 2002; Ramanathan and Carmichael, 2008). It is emitted as a result of the incomplete combustion of fossil fuels, biofuels, and biomass burning, which have both natural and anthropogenic origins. After carbon dioxide (CO₂), BC is recognized as the second-most important climate forcing agent with a total climate forcing of $+1.1 \text{ W m}^{-2}$ (Bond *et al.*, 2013; Schmale *et al.*, 2017). Hence, there has been an increased interest in measuring BC and estimating the ARF using in situ measurements (Badarinath *et al.*, 2004; Nair *et al.*, 2013; Surendran *et al.*, 2013). Several studies in the past have estimated ARF based on in situ measurements in the plain and oceanic regions of the world, but only a few have been undertaken in the glaciated regions (Vinoj *et al.*,

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2004; Moorthy *et al.*, 2005; Marcq *et al.*, 2010). The Himalayas is one such glaciated region of the world, which has been less studied with respect to the impact of aerosols based on in situ measurements. But it is an important source of water and livelihood for approximately 1.4 billion people residing downstream (Viviroli *et al.*, 2007; Immerzeel *et al.*, 2010). The Himalayas also form an orographic barrier, strongly influencing the south-west monsoons. Moreover, the glacier melt in the Himalayas is also accelerated due to surface darkening and atmospheric warming. In this regard, a study by Xu *et al.* (2016) indicates that at Tibetan Plateau altitudes, CO₂ and BC concentrations exerted a warming of 1.7°C and 1.3°C respectively. It concluded that BC, along with CO₂, contributes to snow-retreat trends in the region. This situation becomes even grimmer for the Himalayas as it is surrounded by China and India which are two of the largest emitters of various air pollutants in the region (Kopacz *et al.*, 2011; Kaspari *et al.*, 2014). This may also mean accelerated melting of the glaciers. Hence, it is important to analyse the impact of aerosols on glaciers on a fine scale. However, due to difficult terrains and the high logistics cost involved in setting up a monitoring site, only a few studies have estimated the ARF using in situ measurements in the Himalayan region. Considering the above issues, to date, the BC mass concentration has been measured at only a few high-altitude locations in the Himalayan region. These locations include Hanle (4520 masl) and Meerak (4300 masl) in India, the Nepal Climate Observatory-Pyramid (NCO-P; 5079 masl) in Nepal, and the Qomolangma Atmospheric and Environmental Observation Research Station (QOMS; 4,276 masl) in China (Marcq *et al.*, 2010; Babu *et al.*, 2011; Zhao *et al.*, 2012; Cong *et al.*, 2015; Wang *et al.*, 2016). The forcing estimated at these sites and a few other sites located in the Tibetan Plateau indicates a large variability (Kopacz *et al.*, 2011). Taking into account the scarcity of in situ measurements in high-altitude locations, considerable disparity is also expected in the radiative forcing estimates. Hence, it is essential to undertake more studies over the Himalayan region. In the present study, we calculate the ARF and heating rates near Yala Glacier, Nepal, using in situ BC measurements and outputs from the OPAC and SBDART models constrained by available satellite data sets. In Section 5.1, we discuss the observed BC temporal variation for a period of 8 months. Section 5.2 analyses the local and regional sources using wind roses, CBPF (concentration bivariate probability function) plots and CWT (concentration weighted trajectory) analysis, while Section 5.3 depicts the meteorological impacts. Section 5.4 deals with the optical properties of aerosols. Finally, in Section 5.5, we discuss the ARF over different surfaces and the heating rates at different elevations.

STUDY SITE

The International Centre for Integrated Mountain Development (ICIMOD), in partnership with the Department of Environment (DoEnv), Government of Nepal (GoN), set up an autonomous BC monitoring station near Yala Glacier (28.21°N, 85.61°E; 4900 masl) in October 2016 (Fig. 1). A

digital elevation model (DEM) was used for describing the topography and observation site as shown in (Fig. 1). The station has been set up with the objective of collecting long-term, real-time BC mass concentration data at this location in order to enhance the understanding of climate impacts in the long run. Moreover, the study site also allows for improving the understanding of the inflow of pollutants from the plains into the high-altitude locations. The nearest source of any anthropogenic interference is a small village with a cluster of ~50 households, situated 1 km below (at an elevation of 3900 masl) and approximately 4.3 km south of the observation site. The effects of anthropogenic pollution from this village are rarely expected to show up at the observation site. The landscape around the station is almost flat and is occupied by slight undulations surrounded by grassland and rocks. The seasonal snow cover over the station was observed during the study period. This site is surrounded by mountain peaks and glaciers ranging between elevations 5520 masl and 7234 masl, thus forming a large orographic barrier. The nearest glaciers, Yala and Lirung, are located at an approximate distance of 2 km and 4 km north and west of the site respectively. Hence, the measurements at this site could be considered representative of the glaciers in this region, as shown in Fig. 1. The elevation of the Langtang catchment area ranges from 1459 masl to 7213 masl, with an average altitude of 5169 masl and an area of 353.6 km². Out of the total catchment area, 39% is covered by glaciers while the remaining 61% is covered by rocks and vegetation (Pradhananga *et al.*, 2014).

MATERIALS AND METHODS

Autonomous BC Monitoring Station

The autonomous BC monitoring station was installed in October 2016 and has been operating to date to monitor real-time BC mass concentration and meteorological parameters. The BC mass concentration measurement presented in this study was carried out during October 2016 to May 2017 using a multi-wavelength Aethalometer (AE33; Magee Scientific Co./Aerosol d.o.o, Slovenia) which employs the dual-spot technique for real-time filter loading compensation (Drinovec *et al.*, 2015). It measures the attenuation in the transmitted light at 7 different wavelengths between 370 nm and 950 nm. The instrument was set up to operate at a constant flow rate of 2 L min⁻¹ and the data was recorded at 10-minute intervals. The Aethalometer was factory calibrated and installed for the first time. The BC mass concentration measurement used in the study would represent the changes in optical attenuation at 880 nm employing the mass absorption cross-section 7.77 m² g⁻¹. At 880 nm BC is the prime light-absorbing component of the atmosphere (Hansen *et al.*, 1984; Fialho *et al.*, 2006; Drinovec *et al.*, 2015). As it is an autonomous station, the equipment is powered by batteries and is continuously charged by solar panels. The data are then stored in a data logger that has been fitted into a data collector platform (DCP), from which it is remotely transferred via satellite to the central servers at ICIMOD's head office. A schematic representation of the data acquisition and transmission is shown in Fig. S1.

Fig. 1. (a) Map of the study area showing the Himalayan region and the autonomous BC station represented by red square and (b) The autonomous BC station set up near Yala Glacier.

In order to process the Aethalometer data, different types of corrections such as pressure corrections and C-factor corrections (multiple-scattering corrections), as well as the determination of the appropriate mass absorption efficiency value should be carried out. On performing the pressure corrections using standard equations, the BC mass concentration value reduced by ~50%. Thereafter, the C-factor correction depends strongly on the filter substrate and the mixing state of the BC in aerosols. A value of 2.14 is used for quartz filter (Weingartner *et al.*, 2003) and 1.57 for the TFE-coated glass fibre filter (Drinovec *et al.*,

2015). In the present case, a value of 1.57 was used by the Aethalometer. However, as the location is situated at a high altitude, it is expected to receive aged ambient aerosols in the absence of any nearby sources. Hence, if we use a correction factor of 4.0 (aged ambient aerosols), it would further reduce the values of the BC mass concentration by another ~60% (Schmid *et al.*, 2006). Finally, the location of measurement would also strongly affect the mass absorption efficiency values. As suggested by earlier research, the high-altitude locations in the region have a higher mass absorption efficiency value with an average ranging between

$9.8 \text{ m}^2 \text{ g}^{-1}$ to $14.5 \text{ m}^2 \text{ g}^{-1}$ for Manora Peak and Mount Abu (Ram and Sarin, 2009; Ram *et al.*, 2010). But in the present case, the AE-33 version used a mass absorption efficiency of $7.77 \text{ m}^2 \text{ g}^{-1}$. Hence, if we further correct the same with the high-altitude values used in other research, it would further reduce the BC mass concentration values by $\sim 50\%$, thereby reducing overall the original values by $\sim 90\%$. Hence, if the present 8-month average BC values obtained at the observation site ($481.5 \pm 273.7 \text{ ng m}^{-3}$; Section 5.1) were reduced by $\sim 90\%$ ($\sim 48 \text{ ng m}^{-3}$), it would not be in line with the annual average values presented in the existing literature ($298.8 \pm 341.3 \text{ ng m}^{-3}$ at QOMS; $208 \pm 374 \text{ ng m}^{-3}$ at NCO-P) available for the region. Moreover, similar instruments and methodology have also been used for ambient BC measurements in the nearby high-altitude region (4276 masl) without applying any further corrections (Chen *et al.*, 2018). Considering all the uncertainties associated with the different kinds of corrections, in the present study we have not applied any correction to the instrument-derived data.

Meteorological Measurements

Meteorological parameters such as temperature, relative humidity (RH), solar radiation, pressure, wind speed, wind direction and precipitation were measured at the site

(Fig. 2). A WS301-UMB Smart Weather Sensor (LUFFT, Fellbach, Germany) was installed for measuring temperature, RH, solar radiation and pressure. Wind direction and wind speed were measured using a Wind Monitor-Alpine (Model 05103-45; Young, Traverse City, MI, USA). A Pluvio² (OTT, Loveland, CO, USA) sensor was installed to measure the intensity and amount of precipitation in liquid and solid forms, which is based on the weighing principle. All sensors were installed at particular heights following World Meteorological Organization (WMO) guidelines. All this equipment has been widely used at high-altitude locations considering the harsh weather conditions (Immerzeel *et al.*, 2014; Shea *et al.*, 2015). The equipment was brand new (factory calibrated) and was installed for the very first time.

Satellite Data Sets

The Moderate Resolution Imaging Spectrometer (MODIS) on board the Terra and Aqua satellites provides daily global data on aerosol properties using 36 spectral bands ranging from $0.41\text{--}14.38 \mu\text{m}$ with spatial resolutions of 0.25, 0.5 and 1 km at nadir (Levy *et al.*, 2006). In this study, we have used the MODIS Level 2 3-km aerosol product (Collection 6, MYD04_3K) to retrieve the 550-nm AOD (Levy *et al.*, 2006; Remer *et al.*, 2013) over the Yala Glacier region (28.20°S , 85.60°W , 28.26°N , 85.67°E). The

Fig. 2. Hourly and daily variation in temperature, relative humidity, wind speed, wind direction and daily total precipitation.

present measurements were performed over a high-altitude site (4900 masl) in Nepal. At such a high-altitude location with a complex topography, there is a strong need for the use of fine resolution data. Hence, a 3-km data product was deemed fit for capturing the intricate details over a smaller region. Amongst other data products, at the time of analysis, the MODIS deep-blue algorithm was only available at a 10-km resolution. Hence, we had to use the MODIS 3-km dark-target data product which is globally used and well validated across different regions of the world (Nichol and Bilal, 2016; Gupta *et al.*, 2018; Kumar *et al.*, 2018). There were other data products but those were not suitable to capture the rapidly changing topographical features in this region. Hence, the 3-km dark-target product was used in the present study without applying any corrections. The daily water vapour ($1^\circ \times 1^\circ$) and total columnar ozone ($0.25^\circ \times 0.25^\circ$) data over the Yala Glacier region were obtained from the MODIS on board Aqua, and the Ozone Monitoring Instrument (OMI) respectively (Ramachandran and Kedia, 2010). The surface reflectance values were obtained from the MODIS Aqua Level 3 8-day Global SIN Grid product (MYD09A1). These satellite data sets were downloaded from October 2016 to May 2017 for studying the optical properties and subsequently to simulate radiative forcing. Similarly, the aerosol vertical distribution was derived from the Cloud Aerosol Lidar (Light Detection and Ranging) and Infrared Pathfinder Satellite Observation (CALIPSO) Version 3.3 satellite, which has a spatial resolution of 5 km and Level 2 data set (Dumka *et al.*, 2016). The CALIPSO extinction profiles were downloaded during the study period to understand the distribution of aerosols at an altitude above 4900 masl.

Optical Properties of Aerosols and Clouds (OPAC) Simulation

The OPAC model was used in the present study to simulate the aerosol optical properties (i.e., SSA and AP) near the Yala Glacier region. As an input to the OPAC model, parameters such as aerosol type, height profile, wavelengths, relative humidity and optical properties needed to be defined. The model allows us to define the aerosol mixture in the absence of chemical composition measurements (Vinoj *et al.*, 2004; Satheesh *et al.*, 2008; Pathak *et al.*, 2010). Thus, in the present case, we used the continental average aerosol type based on soot number concentration. The soot number concentration was calculated using in situ BC mass concentration values and aerosol mass per cubic metre of air (M^*) following the methodology suggested by Hess *et al.* (1998). The OPAC model permits the use of RH for 8

different values (0%, 50%, 70%, 80%, 90%, 95%, 98%, and 99%). In the present study, we used the daily mean RH values obtained from the in situ measurements. The height profile of the continental average aerosol type was selected in the OPAC model as defined by Hess *et al.* (1998) where an assumption was made for constant mixing of air and aerosols in the homogeneous atmospheric layer. Keeping the BC number concentration constant, the aerosol components (i.e., water-soluble, water-insoluble and mineral transport aerosol concentrations) were varied until the OPAC-derived AOD and AE were consistent with the MODIS retrievals (Babu *et al.*, 2002; Pant *et al.*, 2006; Kedia *et al.*, 2010; Kaskaoutis *et al.*, 2013) (Table 1). It can be observed in Table 1 that the seasonally averaged AOD, the AE used from MODIS and AOD, and the AE simulated from OPAC were almost similar with an approximate error of $\pm 5\%$. Furthermore, as the AE values simulated from OPAC matched well with the AE values retrieved from MODIS, that in itself suggested that all wavelengths of the AOD also matched well. The reason being that a regression between the AOD spectra and its respective wavelengths (μm) on a log-log scale would produce AE. Hence, the suggestion is that the OPAC-derived results were within the acceptable limits of error and could be used robustly for further analysis. The MODIS-derived AOD has been used earlier to validate the OPAC-derived AOD to determine the robustness of the results (Raju *et al.*, 2016).

Shortwave Aerosol Radiative Forcing Calculation

The ARF was estimated in the shortwave region (0.25–4 μm) using the Santa Barbara Discrete Ordinate Radiative Transfer Atmospheric Radiative Transfer (SBDART) model. It is based on the discrete ordinate approach developed by the University of California, Santa Barbara. The discrete ordinate method considers the transfer of monochromatic, unpolarised radiation in a scattering, absorbing and emitting plane-parallel medium, with a specified bidirectional reflectivity at the lower boundary (Stamnes *et al.*, 2000). SBDART is capable of computing plane-parallel radiative transfer under both clear and cloudy sky conditions within the earth's top of the atmosphere (TOA) and surface (SURF) (Ricchiazzi *et al.*, 1998; Stamnes *et al.*, 2000). In the present case, the model was run for clear sky conditions. Outputs from the OPAC model (SSA and AP), the satellite-derived AOD, surface albedo, columnar water vapour and total columnar ozone were used as inputs for SBDART. The ARF computations were performed with and without aerosols at hourly intervals. The atmospheric forcing was then calculated by subtracting the radiative flux derived with

Table 1. Seasonal mean aerosol optical properties derived from MODIS and OPAC, and seasonal atmospheric forcing (ATM) and heating rate (HR) near Yala Glacier during the study period.

Seasons	MODIS		OPAC		SSA 550 nm	AP 550 nm	F_{ATM} W m^{-2}	HR K day^{-1}
	AOD	AE	AOD	AE				
	550 nm	α	550 nm	α				
Post-monsoon	0.045	1.13	0.044	1.18	0.910	0.677	2.6	0.244
Winter	0.040	1.15	0.042	1.19	0.905	0.670	3.8	0.186
Pre-monsoon	0.058	1.12	0.055	1.17	0.939	0.710	4.9	0.375

aerosols from the radiative flux without aerosols (Moorthy et al., 2005; Kedia et al., 2010; Nair et al., 2013). The ARF at the TOA and SURF is defined as the change in the net flux (down-up) (Haywood et al., 1999; Ramaswamy et al., 2001). The clear sky ARF at TOA and SURF were computed by using the following relation:

$$(\Delta F)_{\text{TOA,S}} = (F_{\text{NA}})_{\text{TOA,S}} - (F_{\text{A}})_{\text{TOA,S}} \quad (1)$$

where F_{A} and F_{NA} are the net fluxes with and without aerosols respectively. The difference between the radiative forcing at the TOA and SURF is expressed as atmosphere forcing (ATM).

$$\Delta F_{\text{A}} = (\Delta F)_{\text{TOA}} - (\Delta F)_{\text{S}} \quad (2)$$

ΔF_{A} represents the amount of energy trapped due to the presence of aerosols within the atmospheric layers (Liou, 2002; Moorthy et al., 2005) where positive forcing indicates the warming potential of the atmosphere. The overall uncertainty in aerosol radiative forcing calculations using SBDART and other input parameters—i.e., in situ BC measurements, OPAC simulations, meteorology and spectral albedo—is estimated to be within 15–20%, as discussed by earlier studies on the Central Himalayas and the urban areas of South Asia (Pant et al., 2006; Panicker et al., 2010).

Heating Rates

The atmospheric heating rate due to aerosol forcing is calculated using the following equation:

$$\frac{dT}{dt} = \frac{g}{C_p} \frac{\Delta F_{\text{A}}}{\Delta P} \quad (3)$$

where dT/dt is the heating rate (K day^{-1}), g is the acceleration due to gravity, C_p is the specific heat capacity of the air, ΔF_{A} is the resultant atmospheric forcing, and ΔP is the atmospheric pressure (Liou, 2002; Kaskaoutis et al., 2013).

METEOROLOGY

The seasonal variation in meteorological features over the Himalayas is both influenced by the local mountain wind system and the south-west Indian monsoon system (Ueno et al., 2008; Bonasoni et al., 2010).

The Central Himalayas generally experience four dominant seasons: the pre-monsoon season (March, April, and May), the monsoon season (June, July, August, and September), the post-monsoon season (October and November), and winter (December, January, and February) (Marcq et al., 2010; Shea et al., 2015).

The meteorological conditions at the observation site for post-monsoon, winter and pre-monsoon seasons starting from October 2016 to May 2017 are shown in Fig. 2. The daily and hourly average variations in RH (%), air temperature ($^{\circ}\text{C}$), wind speed (m s^{-1}), daily total precipitation (mm day^{-1}), and hourly average wind direction ($^{\circ}$) are presented in

separate panels. The mean temperature during the study period was $-4.5 \pm 2.9^{\circ}\text{C}$. The maximum temperature was observed during the post-monsoon season ($-1.6 \pm 0.7^{\circ}\text{C}$) followed by pre-monsoon ($-4.3 \pm 3.1^{\circ}\text{C}$), and the lowest during the winter season ($-6.6 \pm 3.3^{\circ}\text{C}$). Seasonally, the highest RH was observed during the pre-monsoon season ($68.3 \pm 5.7\%$) followed by post-monsoon ($42.2 \pm 38.1\%$), and the lowest during the winter season ($29.1 \pm 3\%$). The higher RH in the pre-monsoon season was a result of convection over the IGPs. The total precipitation was observed to be the highest during the pre-monsoon season ($301.8 \pm 72.7 \text{ mm}$) and the lowest in winter ($39.7 \pm 11.5 \text{ mm}$). The mean wind speed during the study period was observed to be $2.5 \pm 0.2 \text{ m s}^{-1}$ with minimal variation across the different seasons.

RESULTS AND DISCUSSION

Temporal BC Variation

The monthly variation in BC mass concentration during October 2016 to May 2017 is shown as a box-and-whisker plot in Fig. 3. The asterisk symbol (*) in the plot displays the mean, while median, and 25th and 75th percentiles of BC is represented by the central line, lower and upper boundary of the box in each month. While the upper and lower whiskers indicate the maximum and minimum values, the plus sign (+) indicates the outliers. The monthly mean values indicate that the BC mass concentration in the atmosphere was the highest during April ($1123.2 \pm 1088.8 \text{ ng m}^{-3}$) and the lowest during November ($172.7 \pm 95.2 \text{ ng m}^{-3}$). A clear seasonal variation in the BC mass concentration was observed, with the highest in the pre-monsoon season ($707.9 \pm 541.8 \text{ ng m}^{-3}$) and the lowest in the post-monsoon season ($243.7 \pm 132.8 \text{ ng m}^{-3}$). The mean BC mass concentration at the observation site over the 8-month period ($481.5 \pm 273.7 \text{ ng m}^{-3}$) was comparable to the measurements over Hanle and Meerak in India (Babu et al., 2011; Ningombam et al., 2014), NCO-P in Nepal (Marinoni et al., 2013), and QOMS in China (Cong et al., 2015). The pre-monsoon high observed in the present study was also comparable to the findings of other studies conducted at different high-altitude locations in the Himalayas (Carrico et al., 2003; Marinoni et al., 2010; Babu et al., 2011; Srivastava et al., 2012).

The BC mass concentration starts building up through the winter and reaches its peak during the pre-monsoon season. The high concentration during the pre-monsoon season can be attributed to frequent biomass-burning events in the Indo-Gangetic Plains (IGP) during this season, and the uplifting of pollutants from the adjoining IGP to high-elevation regions through convection processes which is due to the high-temperature conditions in the plains (Babu et al., 2011). Apart from that, the long-range transport of aerosols could also play a vital role during this season (Chatterjee et al., 2012; Kumar et al., 2018). Especially during the pre-monsoon season, the Trans-Himalayan valleys act as a channel for transport of pollutants from the IGP to the Himalayas and other high-elevation regions (Dhungel et al., 2018). Similar behaviour was also observed

Fig. 3. The monthly box-and-whisker plots for BC near Yala Glacier region, Nepal, during October 2016–May 2017. The asterisk symbol (*) represents mean concentration while the red line represents median. The bottom and top edges of the box indicate the 25th and 75th percentiles. The whiskers represent extreme data points and plus sign (+) is considered as outliers.

at the NCO-P site by Bonasoni *et al.* (2010). A frequency distribution plot for the daily average BC mass concentration values for the entire duration of this study is shown in Fig. S2. It indicates that the daily average BC values depict a distinct seasonal variability, with the majority of the values remaining within the 250 and 500 ng m⁻³ frequency bin. For only 7% of the days, the daily average BC mass concentration value was observed to exceed 1000 ng m⁻³; this was primarily in the pre-monsoon season. This indicates the presence of transported aerosols. The post-monsoon season's low concentration is mainly due to the fact that this is the period when precipitation decreases, resulting in an almost clean atmosphere.

Diurnal Variations of Black Carbon Aerosols in Different Seasons

The mean seasonal diurnal variation in BC mass concentrations is shown in Fig. 4 (left panel). A distinct diurnal cycle was observed at the study site with gradual increase in concentration soon after sunrise (i.e., ~06:00 local time [LT]), reaching maximum values during the late afternoons followed by lowest concentrations during the nighttime. Such diurnal profiles have also been observed at other high altitude locations in different parts of the world: Hanle, India (Babu *et al.*, 2011); NCO-P, Nepal (Marinoni *et al.*, 2010); QOMS, China (Chen *et al.*, 2018); and the European Alps (Baltensperger *et al.*, 1997). This diurnal variation was pronounced in the pre-monsoon season gradually decreasing by the winters and not distinct in the post-monsoon season. It is also interesting to note here that

wind direction also follows a similar diurnal pattern exhibited by BC (Fig. 4, right panel), thus indicating the strong influence of local meteorology including valley wind flow and planetary boundary layer (PBL) dynamics affecting the diurnal pattern at the study site. The maximum BC concentrations were observed between 12:00 and 18:00 LT during all the seasons. This variation matched well with the PBL changes in the low-lying regions (plains and valleys; Fig. S3), where after sunrise when the boundary layer expands due to heating of the land mass, pollutants along with water vapour find a way to escape from the plains through the valleys and reach up into the high altitudes mixing with the free tropospheric air. Stull *et al.* (1999) also emphasized that during night-time, shallow nocturnal boundary layer act as a cap that restricts the dispersion and mixing of pollutants. After sunrise, heating of the land surface weakens the residual boundary layer and hence disperse the pollutants by convective processes to higher altitudes that have been documented well in the Himalayan region (Marinoni *et al.*, 2013; Dhungel *et al.*, 2018). In order to analyse the effect of PBL height, the same was extracted within the Langtang region (28.21°N, 85.61°E) using ERA5 data product (5th-generation European Centre for Medium-Range Weather Forecasts [ECMWF] reanalysis climate and weather data) during the study period (Fig. 4, middle panel). The reanalysis data was extracted at a horizontal resolution of 0.25° × 0.25° and has been used widely (von Engel and Teixeira, 2013; Hoffmann *et al.*, 2019). Details of the data determining its robustness for use can be found in von Engel and Teixeira (2013). The diurnal

Fig. 4. Seasonal diurnal variation of black carbon, planetary boundary layer height and wind direction near Yala Glacier, Nepal.

pattern of PBL and wind direction (Fig. 4) are in agreement with the fact that during the daytime in the adjacent valleys and plains, when the PBL expands (Fig. S3), it gives a chance for the pollutants to escape to higher altitudes. Further, the south-west wind direction during the daytime very well coincides with the valley wind flow bringing in BC towards the pollutant site and increasing its concentration.

Local and Regional Source Assessment

Impact of Local Wind Speed and Direction on BC Mass Concentration

Wind speed and direction are important factors that influence the atmospheric BC mass concentration. The seasonal wind rose plots (Fig. 5(a)) shown here indicate that the higher frequency of winds predominantly arrived from the SW direction followed by the NE sector, thus indicating a bimodal pattern. Shea *et al.* (2015) have also pointed out that the wind system at the Yala base camp (i.e., the study site) follow a bimodal distribution pattern, with dominant up-valley (SW) and down-glacier (NE) winds. A similar wind flow pattern has also been observed by earlier studies in this region, at Khumbu, Nepal (Bollasina *et al.*, 2002); Langtang, Nepal (Carrico *et al.*, 2003); and NCO-P, Nepal (Bonasoni *et al.*, 2010b). Now, in order to understand the potential sources and distribution of the BC mass concentration with respect to wind direction and speed,

the concentration bivariate probability function (CBPF) analysis was used. The wind rose plots demonstrate that the predominant wind direction was south-westerly. Now, combining wind speed, wind direction and the BC mass concentration, the CBPF plots (Fig. 5(b)) indicate that a higher BC mass concentration was associated with the dominant wind direction at the study site. Primarily during the pre-monsoon season, the up-valley south-west winds bring in different pollutants from the low-lying plain regions (Nepal and the IGP). Previous studies also indicated the role of mountain topography and valleys in transporting the pollutants from the plains to the higher altitudes (Whiteman, 2000), thus indicating the strong role of the transported BC due to higher convection in the low-lying plain regions in the pre-monsoon season. During the post-monsoon season, the atmosphere is relatively cleaner, resulting in lower BC mass concentration, while during winter season, the transport of BC does not seem likely due to temperature inversion and subsidence in the low-lying plain region.

CWT Analysis to Determine Long-distance Sources of BC

While wind rose and CBPF plots indicate the dominant directions from which the higher concentration of BC was arriving, they do not provide appropriate information about the distant sources. Hence, in order to understand the

Fig. 5. (a) Seasonal wind rose plot near Yala Glacier region, (b) Seasonal concentration bivariate probability function plot for BC mass concentrations, (c) Seasonal concentration bivariate probability function plot using relative humidity, and (d) Seasonal concentration bivariate probability function plot using temperature, all measured during October 2016–April 2017 at the observation site.

potential source region of the transported BC (from distant areas) to the receptor site (near Yala Glacier), a concentration-weighted trajectory (CWT) analysis was performed. For this analysis, 5-day air mass back trajectories were generated at 00:00 (UTC) and at an altitude of 100 m above ground level using Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model for the entire study period. Such an analysis has been widely used by researchers (Vinoj *et al.*, 2010; Sen *et al.*, 2017; Mahapatra *et al.*, 2018) in order to understand the source location of the aerosols transported to the receptor site. This analysis has been performed using TrajStat 1.2.2.6, a GIS based software as described in Wang *et al.* (2009). CWT analysis for an individual grid cell (i, j) is an indicator of the source strength of the particular grid cell with respect to the receptor site under study which is given by the following equation:

$$CWT_{ij} = \frac{\sum_{l=1}^L C_i \tau_{ijl}}{\sum_{l=1}^L \tau_{ijl}} \quad (4)$$

where C_i is the concentration of the grid cell with back trajectory index l . L is the total number of trajectories and τ_{ijl} is the time spent in i, j^{th} cell by trajectory l (in other words the residence time of a particular trajectory in each grid cell). A higher value of C_i indicates that the air mass travelling over the i, j^{th} cell would be associated with a higher pollutant concentration at the receptor site. Fig. 6 displays the CWT maps for BC on a seasonal basis during 2016–2017. During the winter season, the major source location of BC is in the west to north-west sectors comprising parts of different high-altitude locations starting from the Karakoram region, the Tibetan Plateau, lowland regions of Nepal and parts of the IGP. However, due to non-conducive meteorological conditions prevailing in the lowland region, the long-range transport of BC is not expected to strongly impact the BC build-up at the receptor site in winter. In the pre-monsoon season, the potential source regions of BC were primarily local in nature and from some parts of Nepal, Bangladesh, the IGP, and the far north-west regions of the study site. Thus, due to a combination of stronger convective activity during the pre-monsoon season and potential local sources of emissions, a higher concentration of BC was observed at the receptor site. As only 0–2% of the trajectories seem to cross the Arabian Sea region in the pre-monsoon season, these can be considered as outliers. Such outliers can also be observed in previous studies performed in the nearby Himalayan region (Marioni *et al.*, 2010; Babu *et al.*, 2011). The post-monsoon season indicates inflow of air from the near and far north-west sectors, which arrive through the nearby high-altitude regions. Simultaneously, this period also coincides with the monsoon decaying phase at the source locations and the observation site. Thus, the long-range transport of BC in this season is not expected to contribute significantly to the BC build-up at the receptor site.

Fig. 6. Seasonal concentration weighted trajectory (CWT) plot for black carbon near the Yala Glacier during 2016–2017. The black dot indicates location of the observational site.

Effect of Meteorological Parameters

Mountain meteorology, in itself, is a complex feature due to the surrounding topography and high altitudes. In the present study, we made an attempt to understand the impact of relative humidity and rainfall on BC variability using scatter plots. Figs. 7(a) and 7(b) depicts the correlation of BC with relative humidity. The scatter plots were created (after removal of precipitation events) for two conditions: (i) relation of $RH < 50\%$ with BC and (ii) relation of $RH > 50\%$ with BC. From the graphs, it is visible that during lower relative humidity ($< 30\%$), the BC mass concentration is observed to be low. Only during moderate relative humidity, the BC mass concentration is observed to be high. A similar phenomena of anomalous RH behaviour has also been observed at a high-altitude urban location in the nearby region (Zalakeviciute et al., 2018).

During the winter season, as cold air moves from the upper atmosphere towards the lowlands, temperature inversion and strong subsidence effects have been observed at a height of 1–3 km from the surface, as a result of which pollutants and water vapour in the adjoining lowland regions, located south of the study site (Rupakheti et al., 2017; Bikkina et al., 2019) get stuck close to the surface, not getting a chance to be transported high up into the valleys reaching the mountain top (Dhungel et al., 2018), thus increasing the surface pollution in the plains and enhancing phenomena like winter fog. However, as the observation site is situated at an altitude of 4900 masl, it receives the free tropospheric cold air that does not contain pollutants and makes the site much drier in the winter season. Hence, primarily during the winter season, along with lower relative humidity, the concentration of pollutants is expected to be lower, which purely represents the free tropospheric air mass at the observation site.

But during the pre-monsoon season, as temperature accelerates drastically in the plains, hot air (along with the pollutants and moisture) tends to rise up and condense due to lower temperatures high in the atmosphere aiding in cloud formation due to the convective processes. While in the process of lifting of pollutants, they find their way

through mountain valleys and reach the mountain tops. Hence, during the pre-monsoon season with a moderate level of relative humidity, the transport of air pollutants from the plain regions is expected to increase the BC mass concentration at the observation site. The same can be well substantiated by the CBPF plots for BC, RH, and temperature (Figs. 5(b)–5(d)). It shows that the winds are prominently arriving from the SW region with a higher load of BC mass concentration and moderate to high RH and temperature. However, during the post-monsoon seasons, though winds arrive from the south-west region, the pollutant concentrations are lower.

Similarly, at a higher relative humidity ($> 90\%$), the BC mass concentration is again observed to be low, which might be due to the scavenging of BC aerosols. During higher humidity conditions, the internally mixed BC aerosols might exhibit a greater hygroscopicity by acting as a cloud condensation nuclei and subsequently get scavenged in the form of cloud droplets. Similar features have also been observed at other high alpine sites (Cozic et al., 2007).

The scatter plot of BC with rainfall (Fig. 7(c)) indicates a negative slope, which provides insights into the scavenging effect. However, the correlation is not strong, which may be due to the non-inclusion of monsoon period data in the present study.

Aerosol Optical Properties

Aerosol Optical Depth (AOD)

The most important optical property of aerosols is the AOD, which is directly proportional to the magnitude of the attenuation of direct solar radiation by the scattering and absorption process (Charlson et al., 1992). AOD is a measure of the extinction of the solar beam by the aerosols distributed within an atmospheric column. The monthly mean AOD, along with its standard deviation, is shown in Fig. 8 (top). In the present study, the mean AOD, derived from the MODIS during the study period (October 2016–May 2017), was observed to be 0.05 ± 0.01 while OPAC derived AOD was found to be 0.047 ± 0.007 . Such lower values are indicative of a cleaner environment typical of

Fig. 7. Scatter plot showing (a) daily average BC mass concentration and $RH < 50\%$ after removal of precipitation events, (b) daily average BC mass concentration and $RH > 50\%$ after removal of precipitation events, (c) daily average BC mass concentration and rainfall during October 2016–May 2017.

Fig. 8. Monthly mean aerosol optical properties with $\pm 1\sigma$ (standard deviation) and surface reflectance near Yala Glacier region during October 2016 to May 2017.

high-altitude locations (Pant *et al.*, 2006; Marcq *et al.*, 2010; Ningombam *et al.*, 2014). The spectral AOD decreases with increase in altitude, and vice versa. The findings from NCO-P, Nepal, revealed AOD values in the range of 0.01 ± 0.00 to 0.10 ± 0.03 (Marcq *et al.*, 2010), while those from Hanle (Verma *et al.*, 2010) and Meerak (Ningombam *et al.*, 2014) were observed to be ~ 0.05 and 0.06 respectively, indicating a similarity in pollution levels at different high-altitude Himalayan locations. The seasonal variation of AOD indicated a pre-monsoon high (0.06), followed by a post-monsoon low (0.05), and falling to the lowest during winter (0.04). The pre-monsoon high AOD values can again be attributed to frequent biomass-burning events in the lowlands, convective lifting and long-range transport of the aerosols (Carrico *et al.*, 2003). The higher AOD observed from satellite data in the pre-monsoon season is also consistent with in-situ observations of a higher BC mass concentration.

Single Scattering Albedo (SSA)

Whether carbonaceous particles principally warm or

cool the atmosphere depends on the aerosol SSA, which is the ratio of the incident radiation that is scattered to the incident radiation that is absorbed. SSA is the ratio of the scattering to the extinction coefficient of aerosols, and is one of the fundamental properties of the aerosol required to determine aerosol radiative forcing (Moorthy *et al.*, 2005; Pant *et al.*, 2006; Chung, 2012). Generally, the SSA value > 0.9 suggests the dominance of scattering aerosols (Kedia *et al.*, 2010; Chakrabarty *et al.*, 2012). This also indicates that extinction results primarily from scattering (Bond and Bergstrom, 2006). However, SSA value < 0.9 indicates the absorbing nature of the aerosols which can contribute to the heating of the atmosphere (Ramanathan and Carmichael, 2008; Praveen *et al.*, 2012).

The OPAC-simulated SSA (at $0.55 \mu\text{m}$) during the study period was estimated to be in the range of 0.905–0.939. The mean SSA during the study period was 0.92 ± 0.02 , indicating the scattering nature of the aerosols. The SSA values derived near the observation site is comparable to the SSA values estimated at other high-altitude sites, i.e., 0.89 at NCO-P, Nepal (Marcq *et al.*, 2010), and 0.98 at

Merak, India (Ningombam *et al.*, 2014). In terms of season, SSA was observed to be higher during pre-monsoon (0.94) followed by post-monsoon (0.90) and winter (0.91).

Despite the higher BC mass concentration during the pre-monsoon season, a higher SSA value can be explained by the presence of higher moisture content in the atmosphere, thus indicating the overall dominance of scattering aerosols. Aerosols can absorb moisture depending on their chemical composition and the ambient RH, which change their phase and growth (Nessler *et al.*, 2005). As RH increases, the radius of hygroscopic aerosols (i.e., water-soluble, mineral-transporting particle) also increases. The increase in the size of aerosols favour a higher SSA (Hess *et al.*, 1998; Ramachandran and Kedia, 2010; Titos *et al.*, 2014). Hence, a higher RH (60.3%) recorded at the observation site during the pre-monsoon season might be responsible for enhancing the scattering nature of the aerosols (Carrico *et al.*, 2003; Howell *et al.*, 2006). The lowest SSA value (0.88) was observed in the month of November, which can be attributed to the lower RH (15.2%) observed in this month.

Ångström Exponent (AE)

The AE is an indicator of aerosol particle size (Ångström, 1964). The values of AE close to 2 indicate the dominance of fine particles associated with combustion by-products, and values less than 1 indicate large particles like sea salt and dust (Schuster *et al.*, 2006; Dumka *et al.*, 2014). The MODIS-derived AE near the Yala Glacier was observed to be in the range of 1.12–1.18, with a mean value of 1.13 ± 0.015 during the study period. While the seasonal average of the OPAC-derived AE was in the range of 1.17–1.19 (Table 1), the monthly values have been shown in Fig. 8. This indicates the presence of fine-mode aerosols over the study site. Ningombam *et al.* (2014)'s study from high-altitude locations also found the higher value (i.e., 1.36 ± 0.18), suggesting the dominance of fine-mode aerosols over the high-altitude Himalayan locations (Dumka *et al.*, 2014; Ningombam *et al.*, 2014).

Asymmetry Parameter (AP)

The AP is the first moment of phase function and an important parameter for calculating radiative transfer (Korras-Carraca *et al.*, 2015). Besides AOD, one of the most important optical properties of atmospheric particles, which is used in radiative transfer, climate, and general circulation models, is the AP. The AP describes the angular distribution of the scattered radiation and determines whether the particles scatter radiation preferentially to the front or back (Haywood and Shine, 1995; Kassianov *et al.*, 2007).

The AP can be obtained by using the measured backscatter fraction (Wiscombe and Grams, 1976). Positive values of the AP denote forward scattering, with values increasing with particle size, whereas negative values indicate backward scattering. In our study, the monthly variations in the AP was in the range of 0.64 to 0.77, indicating the forward scattering of the radiation by atmospheric aerosols. These values were also comparable to that observed by Marcq *et al.* (2010) in the NCO-P site,

Nepal (0.65–0.78), and Ningombam *et al.* (2014) in the Merak station, India (0.68 ± 0.01).

Estimation of ARF and Heating Rate

Seasonal Radiative Forcing

The seasonal mean radiative forcing is presented in Fig. 9. Positive forcing was observed for TOA and atmosphere (ATM), whereas negative forcing was observed at SURF during all seasons. The mean forcing in TOA, SURF and ATM during the study period was estimated to be 3.4 W m^{-2} , -0.5 W m^{-2} and 3.9 W m^{-2} respectively. In terms of season, ATM was estimated to be maximum during the pre-monsoon season (4.9 W m^{-2}), followed by winter (3.8 W m^{-2}), and the lowest in the post-monsoon season (2.6 W m^{-2}). During the pre-monsoon season, TOA and ATM forcing becomes increasingly positive due to the high concentration of aerosols (indicated by in situ BC and AOD values) and surface albedo, implying a greater atmospheric warming potential in this season. Nair *et al.* (2013) suggest that BC and dust are major aerosol components in winter and the pre-monsoon season, which can be attributed to high atmospheric forcing. This corroborates our finding of higher ATM forcing in the pre-monsoon season. Moreover, the MODIS-derived surface albedo was observed to be higher during the pre-monsoon season (0.43) in comparison to the post-monsoon season (0.19) and winter (0.34) due to the snow-covered surface of the Yala Glacier region. Hence, a higher albedo in the pre-monsoon season is expected to enhance the radiative forcing. Positive ATM indicates warming of the atmosphere by absorbing aerosols, whereas negative SURF is attributed to aerosol backscattering and the high surface albedo. The SURF remains negative due to the attenuation of solar flux by the aerosols (Patel and Kumar, 2015). A comparative study of other high-altitude sites within the Hindu Kush Himalayan (HKH) region—NCO-P in Nepal, and Hanle and Meerak in India (Table 2)—indicates similar atmospheric forcing at most locations.

Atmospheric Forcing on Different Surfaces

The earth's surface near the Yala Glacier is covered with snow, rocks or grass, depending on the local conditions and seasonal variabilities as described in Section 4. Thus, it is important to understand the variation in atmospheric forcing which might originate due to differences in surfaces. Hence, on a daily basis, we simulated radiative forcing based on different types of surface parameters. In order to do that, values for different surface albedos were given as an input in the SBDART model. The grass (0.3), snow (0.9) and the rock surface (0.2) albedo were taken from Frenzel (1992) and Voogt and Oke (1998). The mean ATM forcing during the study period for rock, grass and snow surfaces was estimated to be 3.7 W m^{-2} , 4.1 W m^{-2} and 4.3 W m^{-2} respectively (Fig. 10). Lower ATM forcing was observed in the case of rock and grass surfaces, which might be due to lower albedo values for such surfaces. Hence, especially during the pre-monsoon season when the earth's surface is covered by snow near the observation site, atmospheric forcing is observed to be higher (Fig. 10). To summarise, higher surface albedo due to a snow-covered earth surface

Fig. 9. Seasonal variation in mean TOA, SURF and ATM forcing estimated near Yala Glacier region, Nepal, during the study period.

Table 2. Comparison of ARF at different high-altitude sites within the HKH region.

Study sites (masl)	TOA (W m^{-2})	SURF (W m^{-2})	ATM (W m^{-2})	Sources
Near Yala Glacier, Nepal (4900)	+3.4	−0.5	+3.9	Present study
NCO-P, Nepal (5079)	+2.1	−1.6	+3.7	Marcq <i>et al.</i> (2010)
Hanle, India (4500)	+1.7	−1.5	+3.2	Nair <i>et al.</i> (2013)
Merak, India (4300)	−0.4	−6.4	+2.6	Ningombam <i>et al.</i> (2014)

in the pre-monsoon season and higher concentration of aerosols (indicated by higher BC mass concentration and AOD values) support the increase in ATM forcing observed in this season.

Vertical Distribution of Aerosols and Heating Rates

The amount of radiation absorbed/scattered by aerosols

in different layers of the atmosphere influences radiative forcing and subsequently the heating rates (Liou, 2002; Moorthy *et al.*, 2005; Kedia *et al.*, 2010; Dumka *et al.*, 2016). Aerosol radiative forcing largely depends on the vertical distribution of aerosols, the lack of which can introduce unwanted biases into the study (Forster *et al.*, 2007). Hence, in the present case, we used CALIPSO

Fig. 10. Estimated radiative forcing over rock, grass and snow surfaces near Yala Glacier region.

extinction profiles to understand the vertical distribution of aerosols and subsequently calculated the heating rates using the SBDART model (Kedia *et al.*, 2010; Praveen *et al.*, 2012; Dumka *et al.*, 2016). Fig. 11 shows the seasonal distribution of aerosol extinction profiles over the Yala Glacier region. As our observation site was situated at an altitude of ~ 4900 masl, we studied the aerosol extinction above the altitude of 4.9 km only. The seasonal aerosol extinction profiles during winter indicate the presence of aerosol till ~ 7 km elevation, but during the pre-monsoon and post-monsoon seasons, aerosols were observed even up to an altitude of ~ 8 km. Higher aerosol extinction profiles observed during the pre-monsoon season might be attributed to vertical mixing or the long-range transport of aerosols as discussed above (Kovalev and Eichinger, 2004; Dumka *et al.*, 2016). Such processes have been studied in the Himalayan region of Nepal (Dhungel *et al.*, 2018).

Fig. 12 depicts the seasonal heating rate (HR) profiles estimated at a height of 4.9 km over the study site. The HR was observed to decrease with height, which was also commensurate with the reduction in aerosols as the height increased. During the post-monsoon and pre-monsoon seasons, the HR profile extended up to 8 km, while in winter it was limited to 7 km. The mean HR during the study period was estimated to be 0.268 ± 0.117 K day⁻¹. In terms of season, the mean HR was observed to be the highest during the pre-monsoon season (0.375 ± 0.131 K day⁻¹), followed by the post-monsoon season (0.244 ± 0.085 K day⁻¹), and the lowest during the winter season (0.186 ± 0.135 K day⁻¹). The higher HR in the pre-monsoon season over the study site was firmly supported by the higher BC mass concentration and AOD values. The present study findings are comparable with the findings of Marcq *et al.* (2010) from NCO-P, Nepal, where the heating rate was estimated to be 0.2 K day⁻¹ over

the snow surface. Similarly, the study in Merak, India, also revealed the heating rate to be 0.22 ± 0.12 K day⁻¹, indicating the role of aerosols in heating up the atmosphere.

CONCLUSIONS

The present study estimated the aerosol radiative forcing near Yala Glacier region from October 2016 till May 2017 using in situ BC mass concentrations, satellite data sets, and model simulations. The mean BC mass concentration at the study site was observed to be 481.5 ± 273.7 ng m⁻³, with the highest concentration observed in the pre-monsoon season. The diurnal behaviour of the BC mass concentration was strongly influenced by the boundary layer dynamics and valley wind flow patterns. The dominance of south-westerly winds, indicating a valley inflow path, was responsible for increased BC concentrations at the observation site during the afternoons. Based on the air masses arriving at the site, the BC was transported from Karakoram, the Indo-Gangetic Plain, Nepal, and Bangladesh, with the major source regions being Nepal, and Bangladesh, and part of the IGP during the pre-monsoon season. Optical properties of the aerosols indicate higher SSA and AE values suggesting the presence of fine-mode scattering aerosols. The mean aerosol radiative forcing near the Yala Glacier region was estimated to be 3.4, -0.5 , and 3.9 W m⁻² for the TOA, SURF, and ATM, respectively with highest forcing estimated in the pre-monsoon season. The ATM forcing values over rocky, grassy, and snowy surfaces were 3.7, 4.1, and 4.3 W m⁻², respectively, showing that the maximum forcing occurred above highly reflective surfaces (i.e., those covered by snow or glaciers). Upon analysing the CALIPSO extinction profiles, an elevated layer of aerosol extending up to an altitude of 8 km in the pre-monsoon season was detected

Fig. 11. Monthly mean Lidar extinction profiles at 532 nm derived from CALIPSO over the Yala Glacier region for post-monsoon, winter and pre-monsoon seasons.

Fig. 12. Elevation wise seasonal heating rate over the Yala Glacier region for post-monsoon, winter and pre-monsoon seasons using SBDART model.

over the study site. Furthermore, the maximum heating rate, $0.375 \pm 0.131 \text{ K day}^{-1}$, was observed during the pre-monsoon season, compared to a mean heating rate of $0.268 \pm 0.117 \text{ K day}^{-1}$ for the entire study period. Thus, snow-covered surfaces in combination with higher aerosol concentrations increased the ARF and, subsequently, HR values during the pre-monsoon season.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at <http://www.aaqr.org>.

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