Aerosol optical properties over Gurushikhar, Mt. Abu: A high altitude mountain site in India

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Abstract

Continuous and simultaneous measurements of aerosol optical properties (scattering and absorption coefficients) were carried out, for the first time, from a mountain site, Gurushikhar, Mt. Abu in the Aravalli range in western India during the period January 2015 to December 2016. Aerosol scattering and absorption coefficients are higher in the afternoon when compared to forenoon and night because of atmospheric boundary layer dynamics which when accompanied with strong thermal convection aid an upward movement of pollutants to the observational site from the surrounding foothills. Aerosol scattering and absorption coefficients exhibit a strong seasonal variability. The average scattering coefficient during winter, premonsoon, monsoon and postmonsoon was found to be $78.5 \pm 22.9$, $61.8 \pm 12.2$, $49.9 \pm 25.1$ and $121.8 \pm 47.4$ Mm$^{-1}$ respectively. The corresponding absorption coefficients were $14.9 \pm 3.1$, $9.1 \pm 2.9$, $5.1 \pm 3.2$ and $20.2 \pm 10.2$ Mm$^{-1}$. Single scattering albedo exhibits a significant seasonal variation. Single scattering albedo is maximum during monsoon (0.91) and minimum in winter (0.83). Annual mean $\beta_{\text{sca}}$, $\beta_{\text{abs}}$, and SSA at 550 nm are found to be $74 \pm 34$ Mm$^{-1}$, $12 \pm 7$ Mm$^{-1}$ and $0.87 \pm 0.04$. Results indicate that Gurushikhar, a high altitude remote site, is influenced by the local and long-range transported aerosols through convection and advection processes. The observed aerosol characteristics over Gurushikhar are governed more by transport and less by anthropogenic sources, and exhibit less significant inter-annual variability. Thus, Gurushikhar can be considered as a background representative of the nearby source regions as a function of meteorology in western India.

Keywords: Aerosol scattering coefficient, aerosol absorption coefficient, single scattering albedo, mountain site, inter-annual variability.

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INTRODUCTION

Atmospheric aerosols influence the Earth’s radiative budget directly by scattering and absorbing the incoming solar and outgoing terrestrial radiation, and indirectly by influencing the optical properties of clouds and their lifetimes. There has been a substantial interest in studying aerosol properties and their influence on climate over different environments (e.g., ocean (Ramanathan et al., 2001); continental (Jayaraman et al., 2006); urban (Ramachandran and Kedia, 2010)). However, aerosols are still a major source of uncertainty in the prediction of climate change due to the large heterogeneity in aerosol properties, and inadequate information on the variabilities of aerosol characteristics on regional and temporal scales (IPCC, 2007). The uncertainty in the estimation of climate forcing by aerosols can be reduced by studying the seasonal and inter-annual variations in aerosol characteristics over different environments. However, most of the studies on aerosol characteristics are restricted to either urban/semi-urban regions or oceans adjacent to densely populated coastal regions (Kedia and Ramachandran, 2011 and references therein). An analysis of aerosol characteristics measured over a remote high altitude region (mountain) which is far away from the potential sources will be useful to represent regional background. High altitude locations are pristine, and aerosol characteristics over these locations are influenced mainly by the long-range transport (advection and convection processes). Hence, aerosol characteristics over high altitude remote locations can
serve as the background representative of the nearby urban source regions as a function of meteorology.

For the first time, in this work, results from a 2-years analysis of aerosol scattering and absorption coefficients, and single scattering albedo from the high altitude remote site in western India, measured using an integrating nephelometer and a dual spot aethalometer are presented. The results obtained from the study will be important to examine the influence of aerosols over a high altitude remote region in regional scale climate forcing and their global impacts.

SITE DESCRIPTION AND METEOROLOGY

The optical properties of aerosols were measured at Optical Aeronomy Laboratory, Infra-red observatory, Physical Research Laboratory, Gurushikhar (24.65°N, 72.78°E, and 1680 m above mean sea level (AMSL)) (Fig. 1). It is the highest point of the Aravalli Range in the Arbuda Mountains of Rajasthan. The observational site is seen to be influenced by the transport of mineral dust from the Thar Desert (northwestern part of the Indian subcontinent), sea salt from the Arabian Sea (southwestern part of the Indian subcontinent) and anthropogenic aerosols (mainly black carbon) from the Indo-Gangetic Plain (north-northeastern part of the Indian subcontinent) (Fig. 2). The city of Mount Abu (1180 m AMSL) lies downhill from Gurushikhar at a distance of 15 km on a high rocky plateau and surrounded by forests. The city of Mount
Abu is a popular hill station and a tourist destination in the Aravalli range. To the northwest of Gurushikhar lies Abu road (280 m AMSL) at a distance of 40 km in the hills of the Aravalli range which has anthropogenic activity. A famous temple (Guru Dattatrey Mandir), which is situated at an aerial distance of about 450 m from the measurement site, attracts a large number of people during the year. The measurement site is approximately 650 m away from the visitor parking area.

The mean synoptic surface winds over the study region exhibit significant variability in speed and direction (Fig. 2). During premonsoon, the winds originate and travel from the western Indian region, while during monsoon the winds are stronger and moist, and are from the marine (Arabian Sea), and western regions surrounding India. During postmonsoon, the wind pattern starts shifting in direction from southwest to northeast, whereas during winter the surface winds are calm and north-northeasterly. In order to further examine the source regions and the transport pathways of pollutants over Gurushikhar, 7 day (average residence time of aerosols in the lower atmosphere) back trajectory analysis was performed using the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT, version 4.9) model (http://ready.arl.noaa.gov/HYSPLIT.php). Air back trajectories at a receptor site provide vital information about the potential source contribution regions of atmospheric pollutants. The daily trajectory in each month was assigned to clusters according to their magnitude and direction.
using the inherited clustering algorithm (k-mean) in the HYSPLIT model. The number of
clusters is determined from the total spatial variance plot using the HYSPLIT model and each
trajectory cluster signifies the grouping of similar trajectories. Trajectory clustering minimizes
the variability among the trajectories within a cluster and maximizes the variability between the
clusters (Reddy et al, 2012). The cluster mean trajectories and their contributions (percentage)
are computed for each month at 1550 m above ground level (AGL) (~823 hPa) at the
observational site (Fig. 3), as this height is very close to the surface pressure (~830 hPa).

The meteorological parameters (air temperature, relative humidity, and wind speed)
were measured using Vaisala weather transmitter WXT520 at the Gurushikhar, Mt. Abu during
2015-2016. Depending on the prevailing meteorology the entire year has been classified into
four major seasons, namely, winter (December-January-February), premonsoon (March-April-
May), monsoon (June-July-August-September) and postmonsoon (October-November). The
monthly mean air temperature is highest during May (25°C) and lowest during January (12°C)
(Table 1) over Gurushikhar. Relative humidity (RH) is high in August (86%) and is low in
December (25%) (Table 1). The surface wind speeds are maximum in July (4.8 ms⁻¹) and
minimum in December (1.5 ms⁻¹) (Table 1). The rainfall over Gurushikhar is distributed over
the premonsoon and monsoon seasons (Table 1) with maximum rainfall occurring in July (567
mm).
INSTRUMENTS AND MEASUREMENTS

Integrating Nephelometer

An integrating nephelometer (Model No. 3563, TSI Inc., USA) is used to measure aerosol scattering coefficients ($\beta_{\text{sca}}$) at 450, 550 and 700 nm. The instrument draws air sample through an inlet port into measurement volume, where the volume is illuminated by a flash lamp and the scattered light intensity is measured by three photomultiplier tubes kept perpendicular to air flow. The total scattered light is integrated over an angular range of 7-170° from the forward direction. The instrument is periodically programmed for an auto-zero calibration using a high efficiency filter to obtain a measure of clean air signal pertaining to the operating environment. The span calibration is done by passing ultra-high pure CO$_2$ gas and the instrument is regularly calibrated according to the procedure described in operations manual (Model No. 3563, TSI Inc., USA). Measurements of $\beta_{\text{sca}}$ were conducted in a continuous mode with data averaging time of 5 minutes at a flow rate of 20 litres per minute.

Nephelometer measured raw aerosol scattering coefficient ($\beta_{\text{sca(\text{raw})}}$) needs to be corrected for missing forward scattering, and for temperature and pressure variations. The nephelometer performs a truncation of scattered radiation at < 7° scattering angle and this missing forward scattering is corrected following Anderson and Ogren (1998) as

$$\beta_{\text{sca}} = \beta_{\text{sca(\text{raw})}} C_{ts}(\lambda)$$
where $\beta_{\text{sca} \text{ (raw)}}$ is the raw scattering coefficient, $C_{ts}(\lambda)$ is the correction factor, and $\AA$ is Angström scattering exponent, and represented as

$$\AA = \frac{-\ln(\beta_{\text{sca}}(\lambda_2)/\beta_{\text{sca}}(\lambda_1))}{\ln(\lambda_1/\lambda_2)}.$$ 

The nephelometer is calibrated at standard temperature and pressure (STP), and variations in temperature and pressure from STP are corrected following

$$\beta_{\text{sca}} = \beta_{\text{sca}} \left(\frac{T}{273.2}\right) \frac{1013.2}{P}$$

where $T$ is absolute temperature (K) and $p$ is pressure (hPa). The overall uncertainty in $\beta_{\text{sca}}$, taking into account the above sources of uncertainty is estimated to be about 15%.

**Dual spot aethalometer**

Aethalometer is an optical attenuation based instrument used for the measurement of aerosol absorption coefficient in ambient air. It primarily gives black carbon (BC) mass concentration at 7 wavelengths (370, 470, 520, 590, 660, 880 and 950 nm) which is further converted to aerosol absorption coefficient ($\beta_{\text{abs}}$) using mass specific attenuation cross section (Rajesh and Ramachandran, 2018). The single spot aethalometers were found to exhibit non-linearity due to aerosol loading effect (Arnott et al., 2005; Weingartner et al., 2003; Virkkula et al., 2007), and hence, in order to compensate for the non-linearity in real-time BC mass concentration measurements, aethalometer based on dual spot attenuation measurement technique was
developed (Drinovec et al., 2015). In the dual spot aethalometer (Magee Scientific, AE33), simultaneous measurements are obtained from two independent sample spots with respect to a blank reference filter spot and each sample spot has different flow rates (Drinovec et al., 2015). The outputs from both the sample spots are then combined to eliminate non-linearity and further used to estimate the compensated aerosol light attenuation to provide real-time BC mass concentration (Rajesh and Ramachandran, 2018). The light attenuation through the sample spots can be parameterized by a non-linear empirical relationship given by Gundel et al. (1984) as

\[
\begin{align*}
ATN1 &= \frac{1}{k} \left( 1 - e^{-kB_1 \sigma} \right) \\
ATN2 &= \frac{1}{k} \left( 1 - e^{-kB_2 \sigma} \right)
\end{align*}
\]

where \( k \) is filter loading effect compensation parameter, \( B_1 \) and \( B_2 \) are the aerosol loadings on the two independent sample spots. \( k \) is estimated in real-time using the above equations as

\[
\frac{F_2}{F_1} = \frac{\ln(1 - k ATN2)}{\ln(1 - k ATN1)}
\]

where \( F_1 \) and \( F_2 \) are the volumetric flow rates through the individual sample spots. The filter loading effect compensated black carbon mass concentration is estimated using the attenuation measured on the spot with higher flow as

\[
BC = \frac{A \{ d (ATN1)/100 \}}{F_1 (1 - \varnothing) \sigma C (1 - kATN1)dt}
\]
where $\phi$ is the lateral airflow in the filter matrix and is estimated with measured input and output flow rates ($F_{\text{input}} = F_{\text{output}}(1 - \phi)$), $A$ is the sample spot area, $C$ is enhancement parameter that arises due to multiple scattering effects; for Teflon coated fibre filter $C$ is 1.57. $\sigma$, is the mass specific attenuation cross section which is instrument dependent and varies as a function of wavelength (Rajesh and Ramachandran, 2018). Aerosol absorption coefficient ($\beta_{\text{abs}}$, Mm$^{-1}$) is further computed as

$$\beta_{\text{abs}} = BC \sigma.$$  

The dual spot aethalometer (AE33) was operated at a flow rate of 3 litres per minute with the time base of 1 min. The total uncertainty in $\beta_{\text{abs}}$ due to variation in filter scattering because of aerosol loading, sample flow rates, filter spot area and detector response is estimated to be about 10% (Rajesh and Ramachandran, 2018). The absorption coefficient at 550 nm is derived using the absorption coefficients measured at 7 wavelengths (370, 470, 520, 590, 660, 880 and 950 nm) following the wavelength dependence of $\beta_{\text{abs}}$ (Rajesh and Ramachandran, 2018).

Both the instruments were sampling the ambient air through a common manifold with sampling inlet mounted 10 m above ground level. A total of 524 and 536 days of $\beta_{\text{sca}}$ and $\beta_{\text{abs}}$ data were available during the 2-year period which are analysed. The data gaps occurred due to raw power failure, UPS failure, and maintenance of instruments (Table 2).

**RESULTS AND DISCUSSION**
Diurnal characteristics

The scattering ($\beta_{sca}$) and absorption ($\beta_{abs}$) coefficients represent the attenuation of the solar radiation due to scattering and absorption by aerosols respectively. The aerosol optical properties (scattering ($\beta_{sca}$) and absorption ($\beta_{abs}$) coefficients at 550 nm) exhibit atypical diurnal variability (Figs. 4 and 5) different than the diurnal variability observed over any source region (e.g. urban (Ramachandran and Kedia, 2010)). Typically over an urban site high values of $\beta_{sca}$ and $\beta_{abs}$ are reported during morning (07-09 local time hrs) and late evening (19-21 hrs) due to the substantial increase in the anthropogenic activities and the atmospheric boundary layer dynamics, which decreases as day advances (due to the evolution of the atmospheric boundary layer) and attains its minimum value around 15-16 hrs (Ramachandran and Kedia, 2010). On the contrary, $\beta_{sca}$ and $\beta_{abs}$ over Gurushikhar show a late afternoon maxima and a midnight minimum. This odd diurnal feature in aerosol characteristics arises due to the evolution of the atmospheric boundary layer which transports the pollutants from the foothills to the observational location during the afternoon hours. During daytime, after the sunrise, the land gets heated up which results in the convective motion of the air parcels (Kovalev and Eichinger, 2004), which in turn increases the vertical mixing of air and results in the higher values of $\beta_{sca}$ and $\beta_{abs}$ at the study location. The observations reveal that vertical transport of pollutants from the valley regions by the evolving atmospheric boundary layer modulates the aerosol
concentration at the observational peak. Hence, the observed $\beta_{sca}$ and $\beta_{abs}$ during the afternoon hours are higher than forenoon (Figs. 4 and 5). $\beta_{sca}$ and $\beta_{abs}$ show similar variations over the measurement location (Figs. 4 and 5), however, $\beta_{sca}$ is higher than $\beta_{abs}$ by a factor of 6 throughout the year. The difference between the maximum and the minimum value of the day is called as the diurnal amplitude. The maximum amplitude of diurnal variation in $\beta_{sca}$ and $\beta_{abs}$ are ~54 and 10 Mm$^{-1}$ respectively during January. January is the coldest month; because of colder temperatures people burn biomass materials to keep them warm throughout the hills resulting in an increase in the anthropogenic/biomass burning emissions. The minimum amplitude of diurnal variation in $\beta_{sca}$ and $\beta_{abs}$ are ~6 and 2 Mm$^{-1}$ during March respectively (Figs. 4 and 5) probably due to the minimum influence of the anthropogenic emissions at the observational site. The maximum (54%) contribution of long-range transport of the air parcels are from the non-fire affected areas (Fig 3). These effects may give rise to minimal diurnal amplitude during March.

Single scattering albedo (SSA), defined as the ratio between the scattering coefficient ($\beta_{sca}$) and the extinction (sum of scattering ($\beta_{sca}$) and absorption ($\beta_{abs}$)) coefficient of aerosols, can range from 0 (purely absorbing aerosols) to 1 (purely scattering aerosols). A higher SSA indicates the dominance of scattering aerosols as compared to the absorbing aerosols in the aerosol distribution. The maximum relative standard error in the estimated value of SSA is <10%. SSA at 550 nm over Gurushikhar also exhibits a rare diurnal variability (Fig. 6) different
than the variability observed commonly at other environmentally distinct locations (Ramachandran and Kedia, 2010 and references cited therein). Typically, over an urban location SSA shows two minima during the morning (07-09 hrs) and evening (19-20 hrs) coinciding with morning and evening $\beta_{sca}$ and $\beta_{abs}$ peaks due to the dominance of absorbing aerosols from the anthropogenic activities, and an afternoon maximum as absorbing aerosol emissions decrease. The SSA decreases sharply after 21 hrs due to the consistent decrease in $\beta_{sca}$ (Fig. 4). This peculiar behaviour in SSA is probably due the characteristic feature of the influence of local/regional meteorology which consistently decreases the supply of scattering type aerosols to the observation location.

**Monthly and seasonal characteristics**

The high altitude observational site (Gurushikhar) has been found to have minimum or negligible anthropogenic emissions. The aerosol scattering ($\beta_{sca}$) and absorption ($\beta_{abs}$) coefficients at 550 nm decrease from January to April and then increase during May and June, which again decrease afterward till August and then increase from October to November before becoming low in December (Figs. 7a and 7b). The maximum $\beta_{sca}$ (155.3 Mm$^{-1}$) and $\beta_{abs}$ (27.4 Mm$^{-1}$) are observed during November as in addition to the anthropogenic emission from the nearby region, it is strongly influenced by the long-range transport (77%) from the northern part of India (Fig. 3). The factors causing high aerosol scattering and absorption coefficients are due
to transport through convective (transport from the foothills) and advective (long-range transport) processes. The minimum $\beta_{sca}$ (26.3 Mm$^{-1}$) and $\beta_{abs}$ (2.8 Mm$^{-1}$) are observed during August due to the removal of aerosols by precipitation (Table 1). $\beta_{sca}$ and $\beta_{abs}$ show a strong seasonal variation over Gurushikhar. $\beta_{sca}$ and $\beta_{abs}$ are highest during postmonsoon (121.8 and 20.2 Mm$^{-1}$) followed by winter (78.5 and 15.0 Mm$^{-1}$), as the location is affected significantly by convection and advection (Fig. 3). In addition, during postmonsoon and winter there is a significant increase in the amount of biomass burning, and the tourist activities (resulting in an increase in vehicular emission) in the region. $\beta_{sca}$ and $\beta_{abs}$ decrease during premonsoon due to the change in the wind direction and source region (arid to marine). The minimum $\beta_{sca}$ (49.9 Mm$^{-1}$) and $\beta_{abs}$ (5.1 Mm$^{-1}$) are observed during monsoon due to the wet removal. The cluster distribution shows that during monsoon winds are entirely from the Arabian Sea, whereas, during postmonsoon the air are from the fire affected areas (Punjab and Haryana) (Fig. 3). During winter the maximum cluster contributions are from the land mass (75%, 85% and 71% in December, January and February) (Fig. 3), whereas, premonsoon exhibit the changes in wind direction from March to May (Fig. 3). During May the maximum air parcels are from the Arabian Sea which resulted in higher contribution of aerosol scattering coefficient as compared to aerosol absorption coefficient (Figs 4 and 5). The annual mean $\beta_{sca}$ and $\beta_{abs}$ are found to be 74 and 12 Mm$^{-1}$ respectively over Gurushikhar. It is interesting to note that monthly mean
variability of $\beta_{\text{sca}}$ is different than that of $\beta_{\text{abs}}$, but the seasonal mean $\beta_{\text{sca}}$ and $\beta_{\text{abs}}$ go hand in hand. Annual mean $\beta_{\text{sca}}$ (78.8 Mm$^{-1}$) found over Gurushikhar is lower than the values reported over an urban location in western India (Ganguly et al., 2006). Gurushikhar $\beta_{\text{sca}}$ is also found to be lower than various urban, sub-urban, rural, and mountain sites in China (Li et al., 2017).

Single scattering albedo (SSA) also exhibits significant monthly and seasonal variations (Fig. 7c). The maximum SSA (0.93) is observed during May as 95% of the long-range transported air masses are from Thar Desert and Arabian Sea (Fig. 3) which bring in more scattering type aerosols relative to the anthropogenic emissions from the valley/footills. Whereas, the minimum SSA (0.82) is found during December as 85% of the long-range transported air are from the northern regions of India (Fig. 3) which brings in more absorbing type aerosols (black carbon) as compared to the contributions from the nearby valley regions. SSA decreases from July to December indicating a transition from the dominant scattering type aerosols to absorbing type aerosols.

In order to examine the spatial distribution of potential biomass burning sources which produces black carbon aerosols, which can influence aerosol absorption and SSA at the observational site, MODIS cloud corrected fire count version 5 monthly data available at 1ºx1º resolution have been examined (Fig. 3). Fire counts exhibit large spatial variations over India (Fig. 3). The area infested by forest fires and biomass burning is high during winter and
premonsoon as compared to monsoon and postmonsoon. During postmonsoon, Punjab and Haryana show high fire counts due to relative dominance of biomass burning (residue crop burning). In addition, premonsoon shows higher fire counts in the Indo Gangetic Plains due to residue crop burning during this period over Punjab and Haryana (Fig. 3). The wind patterns play an important role in transporting the biomass aerosols from the biomass burning regions to the observational site through advection process (Fig. 3).

Low SSA during March and April reveals the dominance of absorbing type aerosols which get transported from the residue crop burning areas in Punjab and Haryana. SSA in March is marginally lower than April because 54% of air trajectories originate from the residue crop burned source regions during March when compared to April. The MODIS fire count map shows highest fire density during May in the Punjab and Haryana region of northern India (Fig. 3) but this signature is not observed over Gurushikhar as only 3% of the air parcels reaching the observational site are from this hot spot region, and 95% of the air trajectories are from the arid regions and Arabian Sea (Fig. 3). Highest SSA (0.90) is observed during monsoon followed by premonsoon (0.87) and postmonsoon (0.86) (Table 3). Minimum SSA (0.84) is observed during winter due to the dominance of the absorbing type aerosols arriving the observational site from the northern region of India. SSA is in the range of 0.83 to 0.91 with an annual mean value of 0.87 at 550 nm over Gurushikhar.
The seasonal mean $\beta_{sca}$ values observed over Gurushikhar are significantly lower than a nearby urban source location (Ahmedabad, situated at a distance of 200 km) by a factor of 3 during winter and by a factor of 2 during premonsoon, monsoon and postmonsoon seasons. Unlike Gurushikhar, the highest $\beta_{sca}$ over Ahmedabad was observed during winter ($240 \text{ Mm}^{-1}$) followed by postmonsoon, premonsoon and monsoon seasons (Kedia, 2010). A similar pattern in $\beta_{sca}$ and $\beta_{abs}$ was observed over another urban location (Delhi) in the Indo Gangetic Plains with very high magnitude during winter (7 and 12 times higher than Gurushikhar $\beta_{sca}$ and $\beta_{abs}$ values respectively) (Soni et al., 2010). The SSA during December is lower than the SSA reported over a cleaner site Manora Peak, a high altitude site in the central Himalayas (0.90) (Pant et al., 2006). Annual mean SSA over Gurushikhar is significantly higher than those reported over Ahmedabad (0.78) (Ganguly et al., 2006), Delhi (0.70) (Soni et al., 2010), and Visakhapatnam (0.76) (Niranjan et al., 2011).

$\beta_{sca}$ and $\beta_{abs}$ exhibit less significant inter-annual variability (Figs. 7a and 7b). The observed monthly percentage change in $\beta_{sca}$ and $\beta_{abs}$ between 2015 and 2016 is $< 15\%$ (Figs. 7a and 7b) which is within the uncertainty of the measurements. A two-tailed p-value is found to be $< 0.05$ between the SSA data for each month during 2015 and 2016, which confirms the significant inter-annual differences. The inter-annual differences in SSA between 2015 and 2016 are found to be lower than 10% which is less than the uncertainty in SSA estimate (15%). The high altitude
remote observational site (Gurushikhar) has minimal anthropogenic sources and the study reveals that aerosol characteristics over this pristine site is influenced mainly by the transport processes (convection and advection). The inter-annual variability in aerosol characteristics estimated for the two year (2015-2016) is found to be less significant and hence, Gurushikhar can be considered as a background representative for aerosols of the nearby source regions in western India.

**Comparison of aerosol properties with other high altitude locations**

Aerosol scattering ($\beta_{sca}$) and absorption ($\beta_{abs}$) coefficients, and single scattering albedo (SSA) show significant variation at other high altitude locations across the globe with differences in their magnitude (Table 4). $\beta_{sca}$ and $\beta_{abs}$ values over Gurushikhar are found to be higher than other high altitude sites, Izana, Spain (Andrews et al., 2011), Mauna Loa, USA (Andrews et al., 2011), Monte Cimome, Italy (Andrews et al., 2011), Mount Lulin, Taiwan (Andrews et al., 2011), Mount Waliguan, China (Andrews et al., 2011), Mukteshwar, India (Hyvärinen et al., 2009), Nepal climate observatory Pyramid (NCO-P) (Andrews et al., 2011), and Whistler, Canada (Andrews et al., 2011) (Table 4), and lower than Nainital, India (Dumka et al., 2015) (Table 4). Most of these high altitude sites exhibit higher SSA (> 0.80) which reveal the dominance of scattering type aerosols (Table 4). The observed variation of $\beta_{sca}$, $\beta_{abs}$, and SSA
values in the high altitude remote site could be due to the prevailing local sources, meteorology
and the long-range transport.

CONCLUSIONS

For the first time, aerosol optical properties (scattering ($\beta_{\text{sca}}$) and absorption ($\beta_{\text{abs}}$) coefficients)

at Gurushikhar (24.65°N, 72.78°E, 1680 m AMSL), Mt. Abu, a high altitude remote location in
western India obtained during the period January 2015 to December 2016 have been analyzed. $\beta_{\text{sca}}$ and $\beta_{\text{abs}}$ were measured using an integrating nephelometer and a dual spot aethalometer respectively. The major findings of the study are -

1. $\beta_{\text{sca}}$ and $\beta_{\text{abs}}$ exhibit peculiar diurnal variability with higher afternoon values as compared
to forenoon and night because of fully evolved atmospheric boundary layer which
accompanied with strong thermal convection aid an upward transport of aerosols to the
mountain site from the surrounding foothills during afternoon hours.

2. $\beta_{\text{sca}}$ and $\beta_{\text{abs}}$ exhibit a strong seasonal variability, and are highest during postmonsoon
(121.8 and 20.2 Mm$^{-1}$) followed by winter (78.5 and 15.0 Mm$^{-1}$), as the measurement
site is influenced by convection from the foothills and advection through long-range
transport; in addition, during postmooon and winter there is a significant increase in the
amount of biomass burning and the tourist activities in the region. The minimum $\beta_{\text{sca}}$
(49.9 Mm$^{-1}$) and $\beta_{\text{abs}}$ (5.1 Mm$^{-1}$) are observed during monsoon due to the wet removal by precipitation.

3. The monthly variability of $\beta_{\text{sca}}$ is different than that of $\beta_{\text{abs}}$, but the seasonal mean $\beta_{\text{sca}}$ and $\beta_{\text{abs}}$ go hand in hand with each other.

4. Single scattering albedo (SSA) exhibits a significant seasonal variation. The maximum SSA (0.91) is observed during monsoon followed by premonsoon (0.90), postmonsoon (0.86) and winter (0.83).

5. $\beta_{\text{sca}}$, $\beta_{\text{abs}}$ and SSA do not exhibit any significant inter-annual variability.

6. Gurushikhar has minimal anthropogenic sources and aerosol characteristics are governed more by the atmospheric transport processes (convection and advection).

7. The inter-annual variability in aerosol characteristics is found to be less significant and hence, the high altitude remote observational site (Gurushikhar) can be categorized as a background representative for aerosols of the nearby source regions in western India.

These results correspond to regional background value for western India region, and can be used as a representative inputs in various regional and global climate models for the estimation of climate forcing.

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### Table 1. Mean monthly temperature (T, °C), relative humidity (RH, %), and monthly accumulated rainfall (RF, mm) over Gurushikhar, Mt. Abu during January 2015 – December 2016.

<table>
<thead>
<tr>
<th>Months</th>
<th>T (°C)</th>
<th>RH (%)</th>
<th>WS (ms⁻¹)</th>
<th>RF (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>12.4 ± 2.9</td>
<td>40.0 ± 21.0</td>
<td>1.7 ± 0.9</td>
<td>0.0</td>
</tr>
<tr>
<td>Feb</td>
<td>14.5 ± 3.2</td>
<td>33.6 ± 17.0</td>
<td>1.8 ± 0.8</td>
<td>0.0</td>
</tr>
<tr>
<td>Mar</td>
<td>17.8 ± 3.6</td>
<td>29.8 ± 14.3</td>
<td>1.7 ± 0.7</td>
<td>5.8</td>
</tr>
<tr>
<td>Apr</td>
<td>21.7 ± 2.9</td>
<td>33.5 ± 16.0</td>
<td>3.1 ± 0.8</td>
<td>4.3</td>
</tr>
<tr>
<td>May</td>
<td>25.0 ± 2.8</td>
<td>36.6 ± 17.1</td>
<td>2.9 ± 0.8</td>
<td>8.2</td>
</tr>
<tr>
<td>Jun</td>
<td>24.1 ± 2.8</td>
<td>39.5 ± 18.4</td>
<td>3.6 ± 0.9</td>
<td>221.3</td>
</tr>
<tr>
<td>Jul</td>
<td>21.0 ± 2.0</td>
<td>70.0 ± 15.0</td>
<td>4.8 ± 1.1</td>
<td>567.2</td>
</tr>
<tr>
<td>Aug</td>
<td>18.5 ± 1.9</td>
<td>86.0 ± 12.0</td>
<td>3.2 ± 0.8</td>
<td>322.9</td>
</tr>
<tr>
<td>Sep</td>
<td>17.0 ± 1.8</td>
<td>80.0 ± 11.0</td>
<td>3.3 ± 0.9</td>
<td>8.6</td>
</tr>
<tr>
<td>Oct</td>
<td>16.5 ± 2.1</td>
<td>51.1 ± 13.9</td>
<td>3.2 ± 0.6</td>
<td>0.0</td>
</tr>
<tr>
<td>Nov</td>
<td>16.8 ± 2.3</td>
<td>36.2 ± 16.8</td>
<td>2.6 ± 0.5</td>
<td>0.0</td>
</tr>
<tr>
<td>Dec</td>
<td>15.2 ± 3.5</td>
<td>25.0 ± 16.9</td>
<td>1.5 ± 0.6</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Table 2. The number of days of aerosol scattering ($\beta_{\text{sca}}$) and absorption ($\beta_{\text{abs}}$) coefficients measurements were made over Gurushikhar, Mt. Abu during January 2015 and December 2016. The data gaps are due to power failure, UPS failure, and maintenance of instruments.

<table>
<thead>
<tr>
<th>Months</th>
<th>$\beta_{\text{sca}}$</th>
<th>2015</th>
<th>2016</th>
<th>$\beta_{\text{abs}}$</th>
<th>2015</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>16</td>
<td>29</td>
<td>16</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feb</td>
<td>28</td>
<td>29</td>
<td>28</td>
<td>28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mar</td>
<td>31</td>
<td>31</td>
<td>27</td>
<td>28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apr</td>
<td>22</td>
<td>26</td>
<td>18</td>
<td>22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>May</td>
<td>20</td>
<td>31</td>
<td>15</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jun</td>
<td>15</td>
<td>19</td>
<td>02</td>
<td>02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jul</td>
<td>15</td>
<td>29</td>
<td>15</td>
<td>29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aug</td>
<td>07</td>
<td>19</td>
<td>18</td>
<td>28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sep</td>
<td>00</td>
<td>00</td>
<td>27</td>
<td>26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct</td>
<td>24</td>
<td>25</td>
<td>23</td>
<td>26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nov</td>
<td>20</td>
<td>28</td>
<td>28</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dec</td>
<td>28</td>
<td>31</td>
<td>22</td>
<td>28</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3. Seasonal mean variations of aerosol scattering ($\beta_{\text{sca}}$), absorption ($\beta_{\text{abs}}$) coefficients, and single scattering albedo (SSA) over Gurushikhar during 2015-2016.

<table>
<thead>
<tr>
<th>Season</th>
<th>$\beta_{\text{sca}}$ (Mm$^{-1}$)</th>
<th>$\beta_{\text{abs}}$ (Mm$^{-1}$)</th>
<th>SSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>78.5 ± 23.3</td>
<td>15.0 ± 3.4</td>
<td>0.83 ± 0.03</td>
</tr>
<tr>
<td>Premonsoon</td>
<td>61.8 ± 12.9</td>
<td>9.1 ± 2.4</td>
<td>0.87 ± 0.04</td>
</tr>
<tr>
<td>Monsoon</td>
<td>49.9 ± 25.2</td>
<td>5.1 ± 2.9</td>
<td>0.90 ± 0.03</td>
</tr>
<tr>
<td>Postmonsoon</td>
<td>121.8 ± 35.9</td>
<td>20.2 ± 7.5</td>
<td>0.86 ± 0.01</td>
</tr>
</tbody>
</table>

Table 4. Mean aerosol scattering ($\beta_{\text{sca}}$), absorption ($\beta_{\text{abs}}$) coefficients, and single scattering albedo (SSA) measured over Gurushikhar in comparison with other high altitude sites over the globe.

<table>
<thead>
<tr>
<th>Location</th>
<th>Altitude AMSL (m)</th>
<th>Period (years)</th>
<th>$\beta_{\text{sca}}$ (Mm$^{-1}$)</th>
<th>$\beta_{\text{abs}}$ (Mm$^{-1}$)</th>
<th>SSA</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gurushikhar, India</td>
<td>1680</td>
<td>2015-16</td>
<td>78.0 ± 31.5</td>
<td>12.4 ± 6.6</td>
<td>0.87 ± 0.03</td>
<td>Present study</td>
</tr>
<tr>
<td>Izana, Spain</td>
<td>2400</td>
<td>2008-09</td>
<td>9.3</td>
<td>0.7</td>
<td>0.93</td>
<td>Andrews et al. (2011)</td>
</tr>
<tr>
<td>Mauna Loa, USA</td>
<td>3400</td>
<td>2000-09</td>
<td>1.9</td>
<td>0.1</td>
<td>0.97</td>
<td>Andrews et al. (2011)</td>
</tr>
<tr>
<td>Monte Cimome, Italy</td>
<td>2200</td>
<td>2007-09</td>
<td>17.2</td>
<td>2.5</td>
<td>0.88</td>
<td>Andrews et al. (2011)</td>
</tr>
<tr>
<td>Mount Lulin, Taiwan</td>
<td>2900</td>
<td>2008-09</td>
<td>25.8</td>
<td>2.8</td>
<td>0.90</td>
<td>Andrews et al. (2011)</td>
</tr>
<tr>
<td>Mount Waliguan, China</td>
<td>3800</td>
<td>2005-08</td>
<td>42.5</td>
<td>2.3</td>
<td>0.95</td>
<td>Andrews et al. (2011)</td>
</tr>
<tr>
<td>Mukteshwar, India</td>
<td>2180</td>
<td>2006-09</td>
<td>53</td>
<td>11</td>
<td>0.81</td>
<td>Hyvärinen et al. (2009)</td>
</tr>
<tr>
<td>Nainital, India</td>
<td>1958</td>
<td>2011-12</td>
<td>177</td>
<td>14</td>
<td>0.93</td>
<td>Dumka et al. (2015)</td>
</tr>
<tr>
<td>NCO-P, Nepal</td>
<td>5079</td>
<td>2006-08</td>
<td>17.4</td>
<td>1.6</td>
<td>0.91</td>
<td>Andrews et al. (2011)</td>
</tr>
<tr>
<td>Whistler, Canada</td>
<td>2200</td>
<td>2008-09</td>
<td>4.0</td>
<td>0.5</td>
<td>0.88</td>
<td>Andrews et al. (2011)</td>
</tr>
</tbody>
</table>
Figure Captions

**Fig. 1.** The high altitude observational site in western India – Gurushikhar (1680 m), Mt. Abu, Indo Gangetic Plains, Punjab and Haryana in India (Google Earth image). Google map image shows the spatial layout of Gurushikhar temple, measurement site (Optical Aerosol Laboratory, Physical Research Laboratory (PRL), and the road pathway.

**Fig. 2.** Synoptic average wind stream (ms⁻¹) over India during winter – (a) December, (b) January, and (c) February, premonsoon – (d) March, (e) April, and (f) May, monsoon – (g) June, (h) July, (i) August, and (j) September, postmonsoon – (k) October, and (l) November for 2015–2016. Filled black circles represent the high altitude mountain site, Gurushikhar.

**Fig. 3.** Monthly mean cluster plot over Gurushikhar during winter – (a) December, (b) January, and (c) February, premonsoon – (d) March, (e) April, and (f) May, monsoon – (g) June, (h) July, (i) August, and (j) September, postmonsoon – (k) October, and (l) November for the years 2015 and 2016. The mean trajectory of cluster numbers 1, 2, 3, and 4 are drawn in brown, blue, green, and red colors respectively. Cluster number values represent the percentage of backward air trajectories in each cluster. MODIS active monthly fire counts are also plotted over India during 2015 and 2016. The square box represents the grid containing the significant fire counts.

**Fig. 4.** Monthly diurnal variation of aerosol scattering coefficient ($\beta_{sca}$, Mm⁻¹) over Gurushikhar during winter – (a) December, (b) January, and (c) February, premonsoon – (d) March, (e) April,
and (f) May, monsoon – (g) June, (h) July, (i) August, and (j) September, postmonsoon – (k) October, and (l) November for 2015 – 2016 at 550 nm. Vertical bars represent ±1σ variation about the mean.

**Fig. 5.** Monthly diurnal variation of aerosol absorption coefficient (β_{abs, Mm^{-1}}) over Gurushikhar during winter – (a) December, (b) January, and (c) February, premonsoon – (d) March, (e) April, and (f) May, monsoon – (g) June, (h) July, (i) August, and (j) September, postmonsoon – (k) October, and (l) November for 2015 – 2016 at 550 nm. Vertical bars represent ±1σ variation about the mean.

**Fig. 6.** Monthly diurnal variation of single scattering albedo (SSA) over Gurushikhar during winter – (a) December, (b) January, and (c) February, premonsoon – (d) March, (e) April, and (f) May, monsoon – (g) June, (h) July, (i) August, and (j) September, postmonsoon – (k) October, and (l) November for 2015 – 2016 at 550 nm.

**Fig. 7.** Monthly variation in (a) aerosol scattering coefficient (β_{sca, Mm^{-1}}), (b) aerosol absorption coefficient (β_{abs, Mm^{-1}}), and (c) single scattering albedo (SSA) over Gurushikhar for 2015, 2016 and during 2015-2016 at 550 nm. Vertical bars represent ±1σ variation about the mean.
Fig. 1.
Fig. 2.
Fig. 3.
Fig. 4.
Fig. 5.
Fig. 6.
Fig. 7.