Dynamic Characteristics of Aerosol Optical Properties over Dibrugarh City in the North-Eastern Indian Region during 2018–2021

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ABSTRACT

Aerosols play an important role in the earth's environment across the globe through their involvement in various earth system cycles. The change in the aerosol properties may cause short and long-term impacts, the knowledge of such changes is useful in the estimation of the pollution sources of any region. We have carried out the analysis of the aerosols' optical and radiative properties using AERONET station data from 2018 to 2021 in Dibrugarh City. The higher Aerosol Optical Depth (AOD) values during winter and pre-monsoon months indicate high anthropogenic activities, and biomass burning in Dibrugarh. The impact of various sources and daily meteorological parameters help in understanding the diurnal variations of the AOD, Ångström Exponent (AE), and column water (CW). Fine aerosol fractions dominate the aerosol volume, but sometimes the long-range transport of dust affects aerosol properties during pre-monsoon months (MAM). MODIS-derived AOD and AERONET AOD values show a good correlation, with $R^2 = 0.68$. The highest volume of the aerosols reaches up to $0.11 \ \mu m^3 \ \mu m^{-2}$ during pre-monsoon months, whereas it lies below $0.05 \ \mu m^3 \ \mu m^{-2}$ in other seasons. SSA values indicate the presence of scattering aerosols but in 2020, a sudden decline in the SSA values shows a strong rise in the absorbing aerosols. Throughout the study period (2018–2021), the positive radiative forcing indicates a rise in atmospheric heating.

Keywords: Dibrugarh, AERONET, Aerosols Optical Depth, Ångström Exponent

1 INTRODUCTION

Natural and human activities vary at local and regional scales and impact day-to-day weather and long-term climate, which influence the atmospheric and meteorological processes. The atmospheric aerosols from various natural and anthropogenic sources play an important role in the radiative budget through absorption, diffusion, and scattering of solar radiation along with the change in the cloud properties (Prasad et al., 2007; Derimian et al., 2008; Kaskaoutis et al., 2013; Pani et al., 2016). The change in the radiative budget affects greatly the hydrological cycle (Chauhan and Liou, 2022; Ramachandran and Rupakheti, 2021). The atmospheric aerosols along with greenhouse gases are one of the main sources of climate change (Kaufman et al., 2002; Van Houstan et al., 2021). The atmosphere is dynamic and varies from one location to another location depending on the meteorological parameters (temperature, winds, relative humidity, water vapor) and transport of air mass from surroundings (Bhuyan et al., 2014).

In the last three decades, atmospheric aerosol characteristics in India are studied in detail (Goloub et al., 2000; Singh et al., 2004; Prasad and Singh, 2007, 2009; Singh and Chauhan, 2022). In recent years, atmospheric pollution is increasing due to growing urbanization, industrialization,
anthropogenic activities, and traffic locally and on the highways (Singh et al., 2004; Tripathi et al., 2005; Sarkar et al., 2018, 2019; Singh and Chauhan, 2020). Most of the studies in India focused on the northern, central, and southern parts of India but in the eastern parts of India, long-term analysis of the atmospheric aerosols using ground and satellite observations is limited (Pathak et al., 2010, 2012; Dahutia et al., 2018, 2019).

The eastern part of India (Assam) is close to the international border of China, Myanmar, Bhutan, and Bangladesh and is the hub of the “tea garden”. The surrounding regions cover the oldest oil production field. Assam is considered one of the remote states and is not connected with the capital (Delhi) of India and the other parts, however, with the recent, development of infrastructure, especially road and air networks, the Government of India made efforts to connect this remote area with the other parts.

In the eastern part of India, Assam is one of the largest states, and Dibrugarh is one of the major cities. In this region, biomass burning, oil exploration, oil refineries, tea industries, brick kilns, forest fires, and other anthropogenic emissions are the major sources of air pollution (Pathak et al., 2012). Depending on the seasons and meteorology, the atmospheric conditions in the north-eastern parts of India are influenced by the long-range transport of airmass from all the surrounding regions, especially from the outflow of the Indo-Gangetic Plains, Bay of Bengal, and southern Asian countries (Gogoi et al., 2009, 2011, 2017; Rana et al., 2019; Chauhan et al., 2022; Singh and Chauhan, 2022). Sometimes, the cyclones originated from the Bay of Bengal, after landing on the Indian coast moved to the eastern states, and caused strong aerosol mixing, influencing the aerosol properties of this region (Chauhan et al., 2022). Using limited data from June 2008 to May 2009, Pathak et al. (2010) have shown seasonal and temporal variations of AOD with a maximum AOD during the pre-monsoon season (0.69 ± 0.13 at the wavelength 500 nm in March 2009) and a minimum during the monsoon withdrawal period (0.08 ± 0.01 at the wavelength 500 nm in October 2008). The Ångström Exponent was observed to be highest during the monsoon and pre-monsoon season and lowest during the pre-monsoon and withdrawal monsoon period. Such high values of Ångström Exponent represent smoke from surrounding areas and low values characterize local or long-range transport of dust.

Pathak et al. (2012) have shown a long-term analysis to characterize the aerosol properties over the northeastern part of India using ground MWR (multi wavelength radiometer) data. During the study period, a major influence of the mixed-type aerosols was followed by continental average, urban and biomass burning, and desert dust. These analyses suggest strong seasonal variations during the study period. Pathak and Bhuyan (2014) studied the climatology of the particulate matter using ground observations and suggested that the PM$_{2.5}$ concentrations have a relationship with the fire events and observed a decline in the PM$_{2.5}$ and black carbon (BC) concentration from 2007 to 2012. Pathak et al. (2016a) have also analyzed the transport efficiencies of trace gases and black carbon over Dibrugarh using the Regional Emission Inventory in Asia (REAS) and INTEX-B data. They emphasized the long residual time and long-range transport of the chemical species affecting the northeastern cities of India.

To study the detailed aerosol properties, NASA has deployed the AERONET instrument in many countries throughout the world, which provides quality aerosol data. In India, the first AERONET station was deployed at the Indian Institute of Technology Kanpur campus, under cooperation between NASA and IIT Kanpur which was led by Brent Holben from NASA and Ramesh Singh from IIT Kanpur. IIT Kanpur AERONET station is operational as of January 2001 which provided high-quality aerosol data, which was not available earlier. Since 2018, the NASA AERONET station is operational on the campus of Dibrugarh University (latitude 27.451°N, longitude 94.897°E; Fig. 1) which is located in the upper Brahmaputra basin of north-east India surrounded by Arunachal hills, dense forest, and oil/gas producing wells. This is a unique station to study the influence of surrounding air mass on various aerosol optical properties at Dibrugarh station which was not possible earlier.

During the winter season (December–February), Dibrugarh suffers from dry weather in contrast to wet weather conditions during the monsoon season (June–September) (Pathak and Bhuyan, 2014, 2016b). The rainy days vary up to 25 days during the monsoon season with thick clouds. Arunachal Pradesh is located in the north, about nearly 100 km distance from the study site, and another hill and mountain range to the east and south has rain-bearing monsoon winds to reach this region while preventing access to the cold and dry winds of Central Asia. The hilly topography...
Fig. 1. AERONET is deployed on the campus of Dibrugarh University.

of the area allows unhindered advection only from the IGP in the west or the Bay of Bengal in the southwest and upper-level transportation from regions beyond the hills.

In this paper, we present a detailed analysis of aerosol optical properties derived from the AERONET data which is located in the eastern parts of India for a recent period from 2018 to 2021. This is the first analysis of the dynamics of aerosol parameters observed using the AERONET data in the northeastern state of India. The current analysis of aerosol properties using AERONET data for a short period of four years shows strong seasonal variability and influence of long-range transport of airmass from the surrounding regions. We have also shown the comparison of the satellite AOD observation with the AERONET data for the same study period and with the earlier studies in this region.

2 DATA AND METHOD

For the current analysis, we have used data available through ground and satellite observations.

2.1 AERONET data

The ground observation of the aerosol properties provides support in the calibration of the satellite data. The AERONET project is a ground-based remote sensing aerosol observation
Table 1. The percentage contribution of aerosols at Dibrugarh.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Continental</th>
<th>Dust</th>
<th>Mixed Type</th>
<th>Clean Condition</th>
<th>Anthropogenic Aerosols</th>
<th>Biomass Burning</th>
</tr>
</thead>
<tbody>
<tr>
<td>AOD &lt; 0.7</td>
<td>AE &lt; 1.0</td>
<td>AOD &gt; 0.7</td>
<td>AE = 0.8 to 1.0</td>
<td>AOD &lt; 0.3</td>
<td>AOD = 0.3 to 1.0</td>
<td>AOD &gt; 1.0</td>
</tr>
<tr>
<td>Winter</td>
<td>3.64</td>
<td>0.00</td>
<td>0.97</td>
<td>28.82</td>
<td>62.38</td>
<td>4.17</td>
</tr>
<tr>
<td>Pre-monsoon</td>
<td>7.72</td>
<td>0.02</td>
<td>0.55</td>
<td>15.11</td>
<td>63.16</td>
<td>13.44</td>
</tr>
<tr>
<td>Monsoon</td>
<td>24.91</td>
<td>0.00</td>
<td>0.00</td>
<td>41.64</td>
<td>33.41</td>
<td>0.05</td>
</tr>
<tr>
<td>Post-monsoon</td>
<td>2.02</td>
<td>0.00</td>
<td>0.00</td>
<td>68.87</td>
<td>28.59</td>
<td>0.52</td>
</tr>
</tbody>
</table>

network jointly developed by NASA and PHOTONS (PHOtométrie pour le Traitement Opérationnel de Normalisation Satellitaire; University of Lille, CNES, and CNRS-INSU) (Holben et al., 1998). The data is observed in near-real-time and processed by the NASA team and available at the AERONET web portal (https://aeronet.gsfc.nasa.gov/). Currently, we have used the Version 3, Level 2 dataset with an improved algorithm (Giles et al., 2019). Dubovik and King (2000) and Dubovik et al. (2000) discussed the detailed methodology of retrieving aerosol optical and radiative properties from AERONET stations. The analysis of various aerosol properties (aerosol optical depth, Angstrom exponent, column water, single scattering albedo, volume size distribution, and radiative properties) for the first time is presented in this study. The AERONET station was not operational from July-September 2019, June–September 2020, and February–April 2021 due to due to technical and logistic problems so no data is available during these periods. The source characterization of aerosols was done using AOD and AE values (Tiwari et al., 2018; Rai et al., 2020). The threshold values of AOD and AE for various sources have been discussed in Table 1 following the approach of Rai et al. (2020).

2.2 Meteorological Data

We have considered meteorological data (air temperature, station level pressure, relative humidity, wind velocity, and wind direction) through the Reliable Prognosis (https://rp5.ru/Weather_in_the_world) for the periods 2018 and 2021. This website is designed and supported by Raspisaniye Pogodi Ltd., St. Petersburg, Russia, since 2004. The data is based on the actual observations from 13 observatories and also forecast data. Based on these data, forecasts are prepared by the Meteorological Office of the United Kingdom, which are available through 14 websites under the contract between the Meteorological Office and Raspisaniye Pogodi Ltd. All the data are fully quality-controlled and freely available to the users.

2.3 Satellite Data

For the current analysis, we have also used the Aqua MODIS 550 nm wavelength AOD data. The daily data is averaged over the Dibrugarh with a spatial resolution of 1 km × 1 km. The daily AOD datasets are acquired using Google Earth Engine (https://code.earthengine.google.com/) and the data is provided by the Land Processes Distributed Active Archive Center (LPDAAC) geoportal (a component of NASA’s Earth Observing System Data and Information System (EOSDIS)) (https://lpdaac.usgs.gov/products/mcd19a2v006/).

2.4 Calculation of Radiative Forcing

Using AERONET aerosol retrievals, we have computed shortwave radiative forcing related to the natural and anthropogenic aerosols. Both, the top of the atmosphere (RF_{TOA}) and the bottom of the atmosphere (RF_{BOA}) radiative forcing are estimated. The station-level data provide the RF_{BOA} and RF_{TOA} values, where

\[
RF_{TOA} = F_{TOA}^{\uparrow} - F_{TOA}^{\downarrow}
\]

\[
RF_{BOA} = (F_{BOA}^{\uparrow} - F_{BOA}^{\downarrow})(1 - SA)
\]
where $F_{TOA}$ and $F_{BOA}$ are the fluxes at the top of the atmosphere and bottom of the atmosphere, and the subscripts $a$ and $c$ represent the fluxes with and without aerosols. The arrows show the direction of the flux. $SA$ is the spectral average of the scattering albedo calculated at all four wavelengths of the sun photometer. For the same solar geometry, we have used the data with a Solar Zenith Angle (SZA) of $60^\circ \pm 5^\circ$. García et al. (2012) and Derimian et al. (2008) have discussed in detail the calculation of the radiative forcing using AERONET data.

2.5 Airmass Trajectory Analysis
We have carried out the analysis of long-range transport of airmass using the HYSPLIT trajectory model. For the seasonal analysis of the airmass trajectories, we analyzed the daily backward trajectory over Dibrugarh for 100 hours from 2018 to 2021. Stein et al. (2015) and Rolph et al. (2017) have discussed the details of the HYSPLIT model. For this analysis, we have used Global Data Assimilation System (GDAS) data with a spatial resolution of $1^\circ \times 1^\circ$.

3 RESULTS AND DISCUSSION

3.1 Weather CONDITIONS
We have considered four seasons winter (December–February: DJF), pre-monsoon (March–May: MAM), monsoon (June–September: JJAS), and post-monsoon (October–November: ON). Dibrugarh has a humid subtropical climate with high humidity (99.67%) in July, the highest rainfall (123 mm) in June during the pre-monsoon season, and low humidity (35%, dry) observed during the winter months (DJF) (Fig. S1). The relative humidity during pre-monsoon months varies in the range of 50 to 85%, during monsoon season (JJAS) humidity varies in the range of 60–99%, later with the start of post-monsoon months (ON) gradual decline is observed until the end of the winter season (DJF). From 2018 to 2021, the highest daily temperature is about 30.6°C in July, whereas the highest monthly mean temperature of 30.5°C was observed in August each year. The lowest daily temperature of 14.7°C and the lowest monthly mean temperature of 16.8°C (coldest) are observed in January. The highest daily pressure (756.95 mm Hg) and the lowest (736.06 mm Hg) respectively were observed in January and August. During the pre-monsoon season, a gradual rise in temperature with a gradual fall in air pressure is observed. The pressure shows variations opposite to the temperature. Similarly, the highest monthly mean pressure (753.02 mm Hg) and the lowest (740.65 mm Hg) were observed respectively in December and July. Fairweather and clear skies are interspersed with occasional fog, and haze during the winter season (Pathak et al., 2010).

The sky during the pre-monsoon season looks to be clear and partly cloudy. By the end of March, rainfall continues until the end of the monsoon over the entire northeast. The winter season is relatively short and is the coldest of the year, with a daily average temperature below 22°C. During pre-monsoon season, the temperature varies in the range of 22–26°C, the land surface heats up, and strong convection develops due to the formation of local depressions, especially in the afternoon. The maximum and minimum temperature increases during the monsoon and temperature decreases during the post-monsoon season, with a daily minimum equal to the pre-monsoon season and a maximum of 26°C. The relative humidity level is normally 60%, during monsoon season, and reaches up to 80% and above with winter signifying a subtropical humid environment (Fig. 2).

Wind plays an important role in local climatology and helps in the transportation of air pollutants. During the winter season (DJF), the winds are mostly north to easterly with some fraction of southerly and westerly winds (Fig. S2). During the pre-monsoon season (MAM) the wind direction remains almost the same, but the wind velocity is relatively higher compared to the winter season. During the monsoon season (JJAS), the wind direction varies south-easterly and southerly, and the wind velocity is higher compared to the pre-monsoon season with less calm conditions. During the post-monsoon season (ON), wind velocity and frequency are weaker compared to other months, and wind directions vary from northerly to easterly. During the pre-monsoon to monsoon season, the air mass reaches over the AERONET station from the Indo-Gangetic plains, West Bengal, and southern parts of India. The Indo-Gangetic Plains (IGP) is one of the highly polluted areas, and the outflow (Rana et al., 2019) from the IGP seriously affects the aerosol properties measured at the Dibrugarh location depending upon the meteorological conditions, wind speed, and wind direction.
3.2 Variability of Aerosol Parameters

Fig. 3(a) shows the properties of the aerosols in the wavelength range 340–1600 nm with strong seasonal and inter-annual variability from January 2018–April 2021. A maximum AOD peak (>1) is observed from mid-January to mid-March and the second maxima peak from September to November 2018. In 2019, the maxima peak is observed in February–March, the second peak in May 2019, and no major changes were observed during October and November. In 2020, similar peaks are observed from February–March, afterwards, an increase in AOD is observed during January 2021. These peaks in AOD values are attributed to the natural changes or the variability in the meteorology and transportation of the aerosols (Singh et al., 2004). The pronounced higher concentrations are found during February–April mainly due to changes in sources of aerosols and meteorology (Figs. 1, S1, and S2).

The temporal variation of daily mean AOD (500 nm), column water (CW), and Ångström Exponent (AE; 440–870 nm) is shown in Figs. 3(b), 3(c), and 3(d). The daily mean AOD values during winter and pre-monsoon seasons are mostly higher compared to the monsoon and pre-monsoon seasons. During February and March, the daily mean AOD values are sometimes 2 times the monthly mean AOD values. Fig. 3(c) shows daily variations of AE in the range of 1.0–1.5 from January 2018 to April 2021. The higher AOD (more than 1.5 times during January–March) with a higher Ångström Exponent represents the impact of anthropogenic aerosols (Tiwari et al., 2018). The column water values show strong seasonal variations, CW values from April to May vary in the range of 4–5.5 cm, 5–6 cm during June–August, and more than 6 cm in August (Fig. 3(d)). During other
months, CW values are less than 3.5 cm. Higher values of CW are an indicator of the onset of monsoon and rainfall (Singh et al., 2000; Kumar et al., 2009). For the source characterization, we plotted the AE against AOD (Fig. 3(e)) and categorized the sources into six categories. During the winter season (December to February), the influence of anthropogenic aerosols is observed to be highest (62.38%), followed by clean conditions (28.82%) and biomass-burning aerosols (4.17%). The share of polluted continental (3.64%) and mixed aerosols (3.81%) is quite low (Table 1, Fig. 4).

Fig. 3(a). Wavelength dependency of the Aerosol optical depth in Dibrugarh.

Fig. 3(b). The daily mean AOD (500 nm) from January 2018–April 2021.
The impact of dust loading is not observed in the winter season (AOD > 0.7, AE < 0.8). During pre-monsoon season (March–May), the impact of local anthropogenic aerosols increases and reaches 63.16% whereas the clean conditions decrease and reach 15.11%. A pronounced rise of up to 13.44% is observed in biomass-burning aerosols. The continental Pollutants (PC) increase...
up to 7.72% whereas the mixed aerosols reduce to 0.55%. During this season, the dust aerosols increased to 0.02%. This could be due to the long-range transport of desert dust. We have also analyzed airmass trajectory both in the forward and backward direction. The long-range transport of airmass from the western parts of India has also been observed during this season although

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**Fig. 3(e).** Angstrom Exponent variations with AOD during different seasons. Characterization of Aerosol shows the effect of anthropogenic activities over Dibrugarh.

**Fig. 4.** Percentage variations of different types of aerosol in different seasons.
these events are quite rare (Fig. 5). A detailed discussion of the air mass trajectories (Fig. 5) is in Section 3.5. During the monsoon season (JJAS), contributions of anthropogenic aerosols are 33.41% followed by continental pollution up to 24.91%. In the monsoon season, the clean conditions are found to be highest (41.64%) as the rainfall helps to reduce the aerosol concentration. In the rainy season, biomass aerosols is low limited to 0.05%. In post-monsoon months, the clean conditions increase significantly and reach 68.87% followed by anthropogenic aerosols (28.59%), PC (2.02%), and biomass burning (0.52%) (Fig. 4). The burning of wood and other biomass product is common for cooking and warming houses over the year, except during the monsoon season when biomass and wood are wet (Lhungdim et al., 2006; Rabha et al., 2019). During the pre-monsoon months, the farmers and residents burn the dry grass in the region, so that new green biomass is grown to feed their cows and buffalos.

The diurnal variations of the AOD, AE, and CW are used in various remote sensing data and also used in radiative forcing calculations. For diurnal variation analysis of AOD, CW, and AE, we have analyzed the percentage departure of each data point from the daily means. The unavailability of the data for certain months limits the overall comparison of the seasonal variations of various years. The diurnal variations of aerosol optical parameters and CW are shown in Fig. 6. The maximum
variations in AOD values are seen during the morning and evening hours whereas variations in the afternoon are comparably lower. AOD values show a positive departure before noon and a negative departure in the afternoon time. During pre-monsoon and post-monsoon seasons, the diurnal variability in AOD is lower. The hourly average values are higher in the noontime during winter, pre-monsoon, and post-monsoon seasons (Singh et al., 2004). During monsoon season morning and evening hourly average values are higher which may be due to an increase in anthropogenic activities. The positive shifts in AOD before noon at Dibrugarh is different compared to the other AERONET station in the Indo-Gangetic Plains which show a negative shift (Singh et al., 2004) before noon.

Fig. 6(b) shows diurnal variations of CW. A negative departure is observed in the early morning hours. Between 0730 to 0830 hours, a positive peak is observed in all seasons. Later, a negative maximum departure is observed in the later afternoon and evening time. The diurnal variations are lower during the pre-monsoon months. Based on the hourly average values, the CW values are observed to be highest during monsoon season (JJAS) followed by post-monsoon months (ON) and pre-monsoon months (MAM) (Fig. S3(b)). During DJF, an increase in CW is observed until 1130 hours and afterward, decline until evening. Similar changes are observed during JJAS, but during MAM and ON months, the CW is found to be higher during the morning and afternoon.

The maximum variations in AE values are also seen during morning and evening hours and lower variations are observed between 0930 to 1330 hours. During pre-monsoon, monsoon, and post-monsoon seasons, AE values show a positive shift in early morning hours whereas, during the winter season, the variation is mostly low or negative (Fig. 6(c), Fig. S3(c)). The variations are opposite to the AOD variation. The hourly mean values of AE decrease and shifts toward negative after 8:30 to the daytime in each season. During DJF, the AE values show strong diurnal variability with maxima peaks during morning and evening times due to lower boundary layers (Bhuyan et al., 2014) with low temperatures. In 2018, we even found that the AE values are higher from 0830 hours to 1330 hours, AOD values are also found to be higher in other years. During MAM, the AE shows less variability in comparison to DJF and varies in the range of 1.20–1.40. The morning and evening highs are also the same as DJF but during 2018 and 2021, the values show a significant fall in the evening. During JJAS, AE values are high in the early morning hours.
increase after 1530 hours, this could be due to the rise in anthropogenic activities in the evening. During ON, the AE values are similar during 2018 and 2019 but during 2020, the values show a decline. During 2020, we observe low monthly mean pressure, low wind, high relative humidity, and higher rainfall in Dibrugarh.

Fig. 6(b). Diurnal Variations column water (CW) for different seasons - DJF, MAM, JJAS, and ON during 2018–2021.

Fig. 6(c). Diurnal Variations AE for different seasons - DJF, MAM, JJAS, and ON during 2018–2021.
Fig. 7. Variations of Fine mode fraction (500 nm) with AOD (500 nm) during different seasons.

The relationship between fine mode fraction (FMF) and total AOD can be utilized to discriminate aerosols with similar solar extinction but the difference in sizes such as marine airmass, biomass burning, dust, and others (Suman et al., 2014). For this purpose, we have shown the relationship between the fine mode fraction and total AOD (at 500 nm) for Dibrugarh (Fig. 7) The red dots are showing the FMF with AOD > 0.5 and blue, FMF with AOD < 0.5. During DJF, the dominance of the fine aerosols can be seen as most values are more than 0.5. Also, these fine aerosols with AOD > 1 and FMF > 0.9 indicate the presence of biomass-burning aerosols. During MAM, a significant number of coarse aerosols and fine aerosols are observed and attributed to the aerosols mixing (Xie et al., 2018). During JJAS, scattered patterns show the rise in the coarse particle as the number of scattered points show FMF < 0.5, whereas the AOD values are mostly less than 0.5 which shows the impact of the polluted continental and clean conditions. The fine aerosol concentration is higher during the ON as FMF and AOD values are mostly higher than 0.5. These changes in the FMF and AOD values also strengthen the analysis of aerosols based on AOD and AE values and provide a better estimate of the sources and types of aerosols.

The temporal variations of MODIS-derived daily and monthly mean AOD with daily and monthly mean AOD obtained by AERONET for the period January 2018 to June 2021 are shown in Fig. S4. The average AOD (for the whole study period) is 0.32 using MODIS data whereas the average AOD using AERONET data is 0.42. The maximum and minimum values of AOD are 1.52 and 0.01 by MODIS data and 2.25 and 0.04 by AERONET data respectively. It is seen that the AERONET AOD values are higher in comparison to MODIS-derived AOD. The correlation in MODIS-derived daily mean AOD and AERONET AOD is shown in Fig. 8. MODIS and AERONET data show an R² of 0.684 whereas AOD values are higher using AERONET with respect to MODIS (Fig. 8). The MODIS data is observed twice a day (morning and afternoon) whereas AERONET data provide a full-day measurement. Also, MODIS data can be low bias in the morning and high bias in the afternoon which is also reported in previous studies (Green et al., 2009). Hence, MODIS AOD values are lower in comparison to AERONET at Dibrugarh but both data show a good correlation.

3.3 Particle Size Distribution and Optical Properties

The volume size distribution of aerosols at the Dibrugarh station shows bi-model distribution with strong seasonal variations (Fig. 9a). The maximum volume of aerosols in fine and coarse
Fig. 8. The linear fit of AERONET AOD (500 nm) and MODIS AOD (550 nm) from Jan 2018–June 2021.

The volume size distribution of aerosols from 2018–2021 shows two distinct modes: one in the radius range of 0.11–0.33 µm and another from 2.90–6.64 µm. During DJF, the volume of fine mode particles (< 1 µm) is higher compared to coarse particles, with maxima peaking during 2018, followed by 2020, and 2021. The volume of particles is lowest during the winter season of 2019. During MAM 2019 and 2020, the volume of fine particles is higher compared to coarse particles just like the winter season. During the MAM 2018, we observe a high volume of coarse mode particles (Fig. S5(a)). In this season, only two days (23 and...
25 April 2018) of data are available so we exclude it from seasonal analysis (Fig. 9(a)). On 23 April, the volume of coarse mode particles is higher than the fine mode and on comparing them with the seasonal mean of 2019 and 2020, the volume of both modes is significantly higher (75% in fine mode and 2.77 times in coarse mode) in April 2018. On 25 April, a significant fall in the volume of fine mode aerosols and coarse mode is also observed with respect to 23 April. But on 25 April, the peak in coarse mode shifts from 2.24 µm to 3.86 µm and in fine mode, the peak shifts from 0.19 µm to 0.11 µm. On 25 April, the rise in daily temperature is observed with a fall in pressure, relative humidity, and wind speed. Also, AOD and AE values indicate the presence of mixed aerosols (dust + biomass burning aerosols) (Fig. S5(b)). The 150-hour back trajectory (Fig. S5(c)) shows that change in the source of the airmass on 23 and 25 April 2018 and in the same figure we have also shown the MODIS fire points. During JJAS and ON, the dominance of finer aerosols is observed but this is relatively lower compared to the winter season (DJF). The volume of coarse particles is relatively lower during the whole study period with respect to finer particles. Fine dust particles reach over the AERONET location depending upon the meteorological conditions. The diurnal variations of the size distribution of the aerosols (Fig. 9(b)) are found to be dependent on meteorological conditions, month to month. During the winter months (DJF), from 0700 to 1000 hours, the volume of the particles was found in the range of 0.03 to 0.04 µm³ µm⁻² with the size of particles in the range of 0.113 to 0.225 µm. The second peak of the higher volume of the finer particle is observed in the late afternoon from 1500 to 1600 hours. During this time, a sudden rise in coarse mode particles is observed. During the pre-monsoon season (MAM), the diurnal volume of fine mode particles (0.074 ± 0.044 µm³ µm⁻²) is found to be higher than that of the coarse mode particles (0.060 ± 0.038 µm³ µm⁻²). During morning hours, the volume varies in the range of 0.05 to 0.06 µm³ µm⁻², and enhancement in volume is observed after 1300 hours, up to
0.074 ± 0.044 µm³ µm⁻² (fine mode aerosols). Similarly, the volume of coarse mode particles varies in the range of 0.03 to 0.05 µm³ µm⁻² during the morning hours. It reached 0.060 ± 0.038 µm³ µm⁻² at 1300 hours and remained higher until 1600 hours in the evening. During the monsoon season (JJAS), higher volume is observed during morning and evening hours and the volume is comparable to pre-monsoon months (during morning and evening hours). The data is not available from 0900 to 1200 hours. During post-monsoon months, the volume is lowest concerning other seasons (< 0.02 µm³ µm⁻²). Also, the volume remained stable throughout the day. These conditions suggested that Dibrugarh was mostly impacted by the aerosols due to local anthropogenic activities. Also, forest fire activities (controlled and uncontrolled) are common during MAM in the eastern parts of India and, the fields are prepared for the new crop, so the volume of the finer particles is higher (Badarinath et al., 2009).

### 3.4 Scattering Properties of the Aerosols

Fig. 10(a) shows variations in the seasonal mean of single scattering albedo from 2018 to 2021. During DJF, the SSA values are higher at a lower wavelength and lower at longer wavelengths showing a strong influence of local anthropogenic sources and biomass-burning aerosols. During 2020 and 2021, we found a pronounced decline in SSA values (< 0.90) showing an increase in the absorbing nature of aerosols (Singh et al., 2004). During MAM, the SSA values are higher at a higher wavelength (> 0.90) and lower at lower wavelengths (< 0.90) due to the presence of mixed aerosols in 2018 (Fig. S5(d)). We have also observed similar changes in the volume of particles where we find a higher volume of coarse particles (more than 0.10 µm³ µm⁻²) in 2018. In 2019, the SSA at 440 nm is observed to be lower and afterward shows an increase in SSA values at 675 nm wavelength followed by a decline at higher wavelengths (875 and 1020 nm). Such characteristics behavior of SSA reflects strong mixing of existing anthropogenic aerosols and airmass reaching in the vicinity of the AERONET site from various sources, showing SSA higher than 0.90. During 2020, lower SSA at higher wavelengths and higher SSA at the lower wavelengths (< 0.90) indicate the presence of anthropogenic and biomass-burning aerosols. During JJAS, the SSA values are higher than 0.90 and indicate the presence of aerosols due to local anthropogenic sources and continental air mass. A significant fall in SSA values is observed in 2019 with respect to 2018 during JJAS. During ON, no major change in the scattering properties of the aerosols is observed with respect to JJAS in 2018 and 2019. But in 2020, SSA values and wavelength variability seems...
Fig. 10(b). Diurnal variations of Single Scatter albedo during various seasons.

to be affected more by the aerosols due to biomass burning and anthropogenic sources. Hence the site is mostly influenced by mixed aerosols absorbing in nature (dust and biomass burning) during pre-monsoon months. Later, we investigated the diurnal variations of the SSA in different seasons. The impact of the rise in the local emission is strongly observed (Fig. 10(b)). During DJF (winter months), SSA values are observed to be lower in comparison to other seasons (MAM, JJAS, and ON). During DJF, the SSA values decrease from morning to afternoon and later increase from afternoon to evening. SSA is higher at lower wavelengths and also, especially in morning and evening hours. During MAM and JJAS, the SSA is stable at 440 and 675 nm wavelengths and diurnal variations are observed at 870 and 1020 nm wavelength (fall in SSA values). During ON, the diurnal variations are closer to the DJF, but this time SSA values are higher. So, significant variations are also seen in the diurnal variation in the spectral behavior of the aerosols especially at a higher wavelength with lower SSA due to anthropogenic aerosols along with mixed aerosols.

3.5 Airmass Trajectory

For the estimation of the source of the aerosols reaching the Dibrugarh, we have carried out the analyzed the backscatter trajectory. The daily 100 hours back trajectory over Dibrugarh of each month and each season from 2018 to 2021 are shown in Fig. 5. The trajectory plot supports the variation found in the properties of the aerosol at Dibrugarh. The trajectory shows mostly local airmass is affecting the Dibrugarh. We also found long-range transport of airmass from IGP, northwestern parts of India, and sometimes the Gulf peninsula within 100 hours in DJF and MAM. During JJAS, due to the onset of monsoon, the airmass trajectory shows the source location in the Bay of Bengal and later in ON, again along with local sources of airmass for the long-range transport from IGP. During MAM, the transport from central and western parts of India, the properties of the aerosol show the presence of dust aerosols.

3.6 Instantaneous Radiative Forcing

The monthly mean $RF_{BOA}$ and $RF_{TOA}$ values are observed to be negative during 2018 and 2019 and are shown in Fig. 11. The two-year average of $RF_{BOA}$ is $-52.61 \pm 19.63 \text{ W m}^{-2}$ and the mean $RF_{TOA}$ is $-20.6 \pm 9.41 \text{ W m}^{-2}$. The minimum values of $RF_{BOA}$ and $RF_{TOA}$ are observed during January and March due to the presence of absorbing aerosols because biomass burning either in open
fields or for cooking purposes (Badarinath et al., 2009), absorbs most of the radiation. The maximum values of RF$_{BOA}$ are observed during December whereas the maximum RF$_{TOA}$ is observed during October. The calculated RF$_{ATM}$ is observed to be positive most of the time with an average of $32 \pm 14.64$ W m$^{-2}$ and it is maximum during October 2018. The overall results indicate the warming of the atmosphere over Dibrugarh and the increase in the absorbing aerosols caused more atmospheric heating from January to March.

4 CONCLUSIONS

A detailed discussion of the properties of the aerosol of the Dibrugarh AERONET station has been carried out using the station level and satellite data from 2018 to 2021. This region is mostly affected by the north to easterly winds throughout the study period whereas, during pre-monsoon (MAM) and monsoon (JJAS) months, the west and southerly winds also affect this region. Aerosols properties have shown strong seasonal variations with the highest AOD (1.4) observed in March month. The monthly mean AOD values vary in the range of 0.6 to 1.2 with the lowest during monsoon seasons (JJAS). From January to March, the high anthropogenic activities affect the AE which varies in the range of 1.0 to 1.5 (monthly mean). Sometimes, the long-range transport of plumes from crop burning in Punjab (Kaskaoutis et al., 2014; Chauhan and Singh, 2017; Sarkar et al., 2019) and outflow from the IGP (Gogoi et al., 2011; Rana et al., 2019) influence the aerosol properties (Fig. 5) and strong mixing of the aerosols. The long-range transport of dust is also observed during the pre-monsoon months (MAM) affecting the properties of the aerosol observed at Dibrugarh. The column water shows a strong seasonal pattern and more than 5.5 cm of column water is observed during monsoon months showing the influence of the southern monsoon. The diurnal variations in meteorology and anthropogenic activity show pronounced diurnal variability of aerosols. The current AOD values are higher compared to the observations reported earlier (Pathak et al., 2010) due to growing anthropogenic activities. The fine mode fraction of the aerosols varies in the range from 0.26 to 0.99. The fine mode fraction of aerosols is found to be highest during the winter months and lowest during the pre-monsoon months. MODIS and AERONET
data show a reasonably good correlation with $R^2 = 0.68$ given the poor resolution of MODIS data. MODIS shows low AOD values in comparison to AERONET data since AERONET is a point source representing an average aerosol of a small area compared to the large areas observed from MODIS data. The bi-modal nature of aerosols is observed at Dibrugarh in the range of 0.11–0.33 $\mu$m for fine mode and 2.90–6.64 $\mu$m for coarse particles. During the pre-monsoon months of 2018, the volume of the coarse particles is highest (0.11 ± 0.007 $\mu$m$^3$ µm$^{-2}$) but in other seasons, the volume of the fine particles is found to be higher compared to the coarse particles. The aerosols show mostly high scattering nature at lower wavelengths and low at the higher wavelengths and the impact of mixed aerosols is also visible in SSA values during the 2018 pre-monsoon season. In 2020, the influence of absorbing aerosols is observed and SSA values are lower in all the seasons in the year 2020, this could be due to the COVID-19 pandemic (Chauhan and Singh, 2020) and can be included in future studies. The instantaneous radiative forcing calculation shows heating of the atmosphere due to positive RF values ($RF_{ATM} = 32 ± 19.63$ W m$^{-2}$) and cooling of the surface ($RF_{BOA}$ of $-52.61 ± 19.63$ W m$^{-2}$). These variations in the aerosol properties suggest the impact of biomass burning, local pollution, and other anthropogenic sources.

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SUPPLEMENTARY MATERIAL

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