Estimation of Aerosol Characteristics and Radiative Forcing during Dust Events over Dehradun

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ABSTRACT

Dust storm, a natural hazard, has a direct impact on daily life for a short period. Dust storms are periodic events over India, especially in northern regions. This study has been carried out to investigate the dust impacts on the aerosol characteristics over Dehradun (DDN) during pre-monsoon (March–June), 2012 using ground measurements, satellite observations and model simulations. The measurements illustrate the distinct monthly impact on the aerosol properties with maximum dust loading during May (aerosol optical depth at 500 nm (AOD500) = 0.72 ± 0.18) over DDN, which is confirmed with the Terra-MODIS (AOD550 = 0.70 ± 0.19) measurements. The major dust loading was recorded in aerosol measurements during May at the station, which permitting to examine the influence of dust transports on the aerosol characteristics. Spectral variation of AOD and Angstrom exponent (\( \alpha \)) values displayed day to day variation of aerosol during dust episodes. Analysis of aerosol types and seven-day back-trajectories reveal the transportation of desert dust during May over DDN. The Optical Properties of Aerosols and Clouds (OPAC) model was used to compute the aerosol optical properties (e.g., Single scattering albedo (SSA) and asymmetry parameter (g)) and size distribution. The high values of SSA and g are indicating the dust loading in the atmosphere during May. Aerosol volume concentration at the coarse mode (geometric mean radii (R_V) = 2.89 ± 0.027 \( \mu \)m) is found to be increased in the May, whereas decrement has been observed in the finer mode (R_V = 0.16 ± 0.006 \( \mu \)m). The mean top of the atmosphere (TOA) and surface forcing come out to be –14.49 W m\(^{-2}\) and –53.29 W m\(^{-2}\) respectively in May. The mean net atmospheric radiative forcing (38.79 W m\(^{-2}\) maximum during May) corresponds to heating rate of ~1.06° K d\(^{-1}\) in the atmosphere.

Keywords: Dust storm; MODIS; Volume size distribution; Radiative forcing.

INTRODUCTION

The seasonal variability of the aerosol optical properties and the regional radiative forcing are mainly controlled by aerosol loading, in which dusts are playing an important role in the atmosphere (Tegen and Lacis, 1996). The heterogeneous mixture of dust aerosols causes the considerable uncertainties in quantifying the impact of dust on regional and global climate (Claquin et al., 1998). They enter into the atmosphere mainly through strong wind erosion in arid and semi-arid regions contributing to the long-range transport of dusts, which have been described in several studies using satellite remote sensing and ground observations (Husar et al., 1997; Prospero, 1999; Husar et al., 2001; Prospero et al., 2002; Washington et al., 2003). The characteristics of dust aerosols vary spatiotemporally due to the mixing of local anthropogenic aerosols and variations in regional climate (Seinfeld et al., 2004), which alters the Earth's radiative budget by scattering and absorbing the solar radiation. The attention on aerosol properties over India is found to be increasing and the studies report that the northern part of the India is more influenced by aerosol compared to the southern part of India (Singh et al., 2004; Sarkar et al., 2006; Gautam et al., 2007). Dust storms are a common phenomenon in the Indo-Gangetic Plain (IGP) in the northern region of India during the pre-monsoon (March–June) season (Dey et al., 2004). The IGP has periodically experienced a dust outflow in pre-monsoon season, which are transported by westerly winds from the western (Thar Desert) or northwestern (Arabian countries) regions (Sikka, 1997; Kedia and Ramachandran, 2011). Prasad and Singh, (2007), Singh et al. (2004) and Dey et al. (2004) showed that the dusts have a strong influence on aerosol characteristics over the Indo-Gangetic Plain (IGP). Dust mixes with the local anthropogenic aerosols and alters the optical and radiative properties of aerosols, which highly influence the

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regional climate. It has been reported that the SSA values of dust over India lie between 0.88 and 0.94, which indicates the dust over Great Indian Desert is more absorbing compared to African Dust (Moorthy et al., 2007). Thus, it will be interesting to study how the natural dust aerosols modify the aerosol optical properties and regional radiation budget over Dehradun.

In this paper, we present the variation in aerosol characteristics during dust events and their impact on local radiative forcing over Dehradun, Uttarakhand, India. This study has been carried out using measurements from ground based instruments, satellite observations and model based simulations during pre-monsoon (March–June, 2012). In order to understand the origins of the air masses arriving in the studied region, we performed air mass back trajectory analysis based on the hybrid single particle Lagrangian-integrated trajectory (HYSPLIT). The volume size distribution, single scattering albedo (SSA) and asymmetry parameter (g) are used to study the aerosol characteristics over Dehradun, which are simulated using OPAC model. The estimated outputs from the OPAC model along with observations are integrated into the SBDART model to estimate the aerosol radiative forcing (ARF) at the top of the atmosphere (TOA), surface and within the atmosphere during a dust period.

**STUDY REGION**

Dehradun (30°30′N and 78°36′E) is the capital and district headquarters of Uttarakhand state (Fig. 1). It is located at a mean altitude of 700 m above m.s.l., extends 80 km in length and ~20 km in average width in the Shivalik range of the Himalayas. This region experiences four dominant seasons each year, winter (December–March), pre-monsoon (April–June), monsoon (July–September) and post-monsoon (October–November). During the pre-monsoon season, air mass carries dust particles by southwesterly winds from Thar Desert (Sikka, 1997) and during post-monsoon season, the atmosphere is loaded with black carbon and other fine mode organic particles due to large-scale biomass burning from the Indo-Gangetic plain (IGP) (Kant et al., 2012). In addition to this, the region is influenced by urban pollution from the surrounding populated regions, mining activities (mainly limestone), and forest fires. Since it is a valley, it attracts inversion during significant period of year.

The mean annual rainfall is recorded ~2000 mm, mostly in the monsoon season (15 June–September), that accounts around 70–80% of the total annual rainfall. The relative humidity is observed to be 80–85% during monsoon, less than 55% during pre-monsoon and 60–65% during winter. The average wind speed is generally lower and is less than

![ECMWF derived monthly averaged wind pattern over India for pre-monsoon season. Black dot indicates the study region (Dehradun).](image-url)
4.0 m s⁻¹ and the winds during pre-monsoon (March–June) are predominantly from westerly-north westerly, in monsoon (June–September) are south-south westerly, during post-monsoon (October–November) are westerly-south easterly and during winter (December–February) predominantly are south easterly over the station around the year. Fig. 1 describes the monthly mean wind pattern over India for pre-monsoon season, which indicates the average wind speed is generally low (~3.0 m s⁻¹) and the winds are predominantly from westerly- northerly.

**DATASET AND INSTRUMENTS**

**In-Situ Measurements**

**Sunphotometer Measurements**

The AOD measurements were carried out using a multi wavelength Microtops-II sunphotometer (Solar Light Co., USA) over DDN at five different wavelengths at 380, 440, 500, 675 and 870 nm, from the solar instantaneous flux measurements with its internal calibration using the Langley method. The Full Width at Half Maximum (FWHM) bandwidth for the 380 nm channel is 2.4 ± 0.4 nm and 10 ± 1.5 for the other channels (Morris et al., 2001). An Ozone monitor, which is capable of measuring the total column ozone (TCO) in Dobson units (DU) using three UV channels (305.5, 312.5, 320.0 nm) and the water vapor column (perceptible water content, PWC) in centimeters using two near-IR channels (940 and 1020 nm) as well as AOD at 1020 nm. Thus, the obtained AODs at six wavelengths from both the sets of MICORTOPS-II are utilized to retrieve the Angstrom exponent, which is an index of aerosol size distribution. The Microtops has built in pressure and temperature sensors with GPS connectivity to obtain the position and time coordinates. The calibration factor is multiplied by the radiance signal in the different wavelengths and the absolute value of irradiance is estimated in W m⁻² nm⁻¹. The combined effects of uncertainty contribute to the total uncertainty in the estimated spectral AOD of ~0.01–0.025, which is higher in the UV (Porter et al., 2001). More details of design, performance, error and calibration of Microtops-II is given elsewhere (Porter et al., 2001; Morris et al., 2001; Badarinath et al., 2007).

**Black Carbon (BC) Measurements**

Continuous black carbon mass concentration measurements using a seven-wavelength (370, 470, 520, 590, 660, 880 and 950 nm) aethalometer (model AE-42 of Magee Scientific, USA) were made in Indian Institute of Remote Sensing (IIRS), Dehradun. The instrument was operated at a flow rate of 3 liter per minute for 24 hours day⁻¹ at a sampling rate of 5 minutes. The measurements are made from an altitude of about ~15 meters above the ground using the inlet tube and pump of the aethalometer. The Aethalometer is an instrument that uses a continuous filtration and optical transmission technique to measure the concentration of BC in near-real time. The aethalometer measures BC mass concentrations from the attenuation of a beam of light transmitted through the sample collected on a filter, which is proportional to the amount of BC mass loading in the filter deposit (Hansen and Novakov, 1990). The instrument was factory calibrated and errors in the measurements are around ± 2%.

**Satellite Observations**

**Terra-MODIS**

Satellite datasets (e.g., Terra-MODIS and AURA-OMI) were used along with ground measurements during this study. Moderate Resolution Imaging Spectrometer (MODIS) on-board Terra and Aqua spacecrafts provides daily global data of aerosol properties using 36 spectral bands ranging from 0.41–14.38 μm, with the spatial resolution of 0.25, 0.5 and 1 km at nadir (Levy et al., 2007). Two different algorithms are used to retrieve the AOD from MODIS data over land and ocean (Kauffman and Tanre, 1998). The inversion of observed reflectance using radiative transfer look-up table based on aerosol models is used to derive aerosol properties from MODIS (Remer et al., 2005; Levy et al., 2007). In the present study, collection 5 (C005) Level 3 Terra-MODIS AOD products (spatial resolution 1° × 1°) were obtained from the LADSWEB website (http://ladsweb.nascom.nasa.gov/) on the dusty days.

Surface reflectance characteristics are necessary in addition to aerosol properties to perform accurate aerosol radiative forcing calculations, especially over land regions. Surface reflectance measured by MODIS on-board Terra satellites (8-day, Level 3 Global 500m ISIN grid product, MOD09A1 (Terra)) at seven wavelengths (centered at 0.645, 0.859, 0.469, 0.555, 1.24, 1.64 and 2.13 μm) are used.

**AURA-OMI**

The Aerosol Index (AI) is a significant index for the detection of absorbing aerosols in the atmosphere (Torres et al., 1998). Ozone Monitoring Instrument (OMI) is able to retrieve AI over the globe among many other aerosol and ozone properties via the OMI multiwavelength algorithm (Levii et al., 2006a, b). OMI-AI is successfully derived from both clear and cloudy conditions because it is sensitive to aerosol absorption when it is above the cloud. However, a disadvantage of AI is its strongly dependent on the altitude of aerosols, it is difficult to detect aerosol layer below ~1 km. In this study, NASA OMI science team generated Aura-OMI Level 2G daily gridded AI data products were used.

**Model Based Simulations**

**Seven-Day Back Trajectories**

In order to study the possible source of these aerosols over DDN, seven day air mass back trajectories at 1000, 1500 and 2000 m above the ground level are analyzed for March–May, 2012 using Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Rolph, 2003). The back trajectories were computed for the past 7 days (168 hours), in order to identify the pathways of transported dust. This model is widely used along with aerosol optical properties to identify the regions of aerosol source and aerosol types.

**OPAC Model: Estimation of Aerosol Optical Properties**

Aerosols are mixture of scattering and absorbing types in the atmosphere, their impacts in terms of cooling and
warming of the Earth-atmosphere system depends on several parameters, on which SSA plays a major role (Hatzianastassiou et al., 2005). Except of SSA, the ARF depends mainly on spectral AOD, volume size distribution, water vapor content, ozone amount, asymmetry parameter, surface albedo and vertical distribution of aerosols (Kedia and Ramachandran, 2011). As we do not have the optical properties of the aerosols during the dust period, the Optical Properties of Aerosols and Clouds (OPAC) model (Hess et al., 1998) was used to estimate the optical properties of composite aerosols (volume size distribution, SSA and asymmetry parameters). We have used a mixture of aerosol model (composed of insoluble, water-soluble, soot and minerals transported aerosols). The model iterations were performed until the model simulated spectral AOD and $\alpha$ match with the observed data. AOD, $\alpha$ and BC mass fraction (using Aethalometer) were considered as the inputs of the OPAC model for the construction of aerosol properties. The outputs of this model used as inputs in radiative transfer code for the estimation of aerosol radiative forcing.

**SBDART Model: Estimation of Aerosol Radiative Forcing**

Aerosol radiative forcing (ARF) at both top of the atmosphere (TOA) and surface has been estimated from the difference in the net shortwave solar radiation flux (down minus up) for the aerosol-free (Fna) and aerosol-laden (Fa) atmosphere, which can be expressed as (Moorthy et al., 2005):

$$\Delta F_{TOAS} = (F_{\infty})_{TOAS} - (F_{\infty})_{TOAS}$$

where $\Delta F$ is the net change in radiation flux $F$, and the subscripts TOA and S refer to top of the atmosphere and Earth’s surface respectively. The atmospheric forcing (AFatm) is defined as difference of AFTOA and AFs. In the present study, ARF is computed in the shortwave spectrum (0.25–4.0 $\mu$m) separately for TOA, surface and atmosphere using Santa Barbara Discrete Ordinate Radiative Transfer (SBDART) model developed by Ricchiazzi et al. (1998). SBDART is a plane-parallel radiative transfer code based on the discrete ordinate approach, which is extremely used by investigators to estimate the ARF. The ARF depends on many parameters such as aerosol optical properties, atmospheric conditions and surface albedo. The observations of spectral AOD and $\alpha$ along with OPAC derived SSA and g are integrated into the SBDART model (Ricchiazzi et al., 1998) to simulate the ARF at the surface and TOA at shortwave region. ARF was computed for solar zenith angle at every 5° of interval for a day, when AOD values become available. MODIS derived surface albedo of 0.21 ± 0.009 was integrated in the SBDART as an input for this region.

**RESULT AND DISCUSSION**

**Variation of AOD and Angstrom exponent**

Fig. 2 illustrates the temporal variation of AOD500 and Angstrom exponent ($\alpha_{440-870}$) during pre-monsoon season over DDN. The monthly mean of AOD500 is observed to be high ($\sim 0.72 \pm 0.18$) during May compared to other months. AOD500 has been observed to be > 0.85 after the recorded dust events in the May, which are described in the Table 1 along with the observations of Terra-MODIS derived AOD550, AURA-OMI derived AI and the values of Angstrom exponent. Total five dust events have been recorded (10th, 18th, 20th, 22nd and 26th) during May over DDN. The sudden increment of 0.5–0.7 has been observed in the AOD values on the dust events. Consequently, $\alpha_{440-870}$ Value is noted to be below 0.31 during these dusty days due to the extinction of solar radiation by dust particles in the visible and infrared regions (Hamonou et al., 1999). Total 60–90% increment in AOD and 50–80% decrement in $\alpha$ have been observed during these days.

Spectral variation of AOD illustrates high values at shorter wavelengths, indicating the loading of fine particles in the atmosphere. The presence of dust particle increases AOD in both shorter and longer wavelengths due to enhancement in the interaction of the solar radiation (Schuster et al., 2006), which brings a decrement in the wavelength dependency.

**Fig. 2.** Temporal variation of AOD500 and Angstrom exponent ($\alpha_{440-870}$) during pre-monsoon season over DDN.
Table 1. Ground based and satellite aerosol measurements and its parameters during recorded five dust events over DDN during May, 2012.

<table>
<thead>
<tr>
<th>Dates with the Dust events</th>
<th>AOD$_{500}$ (Microtops-II)</th>
<th>AOD$_{550}$ (Terra-MODIS)</th>
<th>AI (AURA-OMI)</th>
<th>Angstrom Exponent ($\alpha_{440-870}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10th May</td>
<td>0.90</td>
<td>0.83</td>
<td>2.96</td>
<td>0.31</td>
</tr>
<tr>
<td>18th May</td>
<td>1.05</td>
<td>0.95</td>
<td>3.86</td>
<td>0.22</td>
</tr>
<tr>
<td>20th May</td>
<td>0.96</td>
<td>0.90</td>
<td>3.12</td>
<td>0.31</td>
</tr>
<tr>
<td>22nd May</td>
<td>0.99</td>
<td>0.92</td>
<td>3.19</td>
<td>0.28</td>
</tr>
<tr>
<td>26th May</td>
<td>0.87</td>
<td>0.82</td>
<td>3.22</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Fig. 3 describes the spectral dependency of AOD for the study period over DDN. The AOD spectra illustrate a peak during May at both shorter and longer wavelengths, suggesting a dominance of coarse (dust) particles and the weak dependency of AOD. The natural variations in the transport of air mass as well as the variation of meteorological conditions may lead to the extension of the peak, which needs more study with long time datasets.

The monthly summarized values of AOD$_{500}$ and $\alpha_{440-870}$ in box charts providing associated information about the range of values, mean and median (Figs. 4(a) and Fig. 4(b) respectively). The AOD$_{500}$ values are found higher in the range of 0.59–0.91 in the May over DDN. The pattern of AOD$_{500}$ (Fig. 4(a)) over DDN has been found to be similar to the long period climatology studies over Kanpur (Wang et al., 2011) and Delhi (Lodhi et al., 2013), which indicates the characteristics of IGP sites. This pattern illustrates the impact of dust activities over the site during late pre-monsoon (May). The high values of AOD (> 1.0) due to the presence of dust cause the large variation in AOD values in May. The pattern of $\alpha_{440-870}$ (Fig. 4(b)) is common over IGP during pre-monsoon season. The range of $\alpha_{440-870}$ is found to be minimal (< 0.6) during May due to the loading of the dust particles over the observation site. Higher values of $\alpha_{440-870}$ in the rest of the month indicate the variability in the aerosol types, optical properties and the sources.

Aerosol Type Analysis and Transport of the Dust

Aerosols from different sources have different optical and physico-chemical properties, which also depend on wavelength (Dubovik et al., 2002). The relation between two different aerosol properties can help to discriminate the aerosol types (Holben et al., 2001). In this study, the correlation between AOD$_{500}$ and $\alpha_{440-870}$ was used for aerosol discrimination (Kaskaoutis et al., 2007). In this technique, some threshold values are used to discriminate the aerosol types, aerosol range and aerosol characteristics (Kaskaoutis et al., 2009). In the present study, due to the variation in the range of aerosols, synoptic meteorological conditions and the emission sources at the locations, we used slightly different thresholds than Kaskaoutis et al. (2009) used over Hyderabad. The detection of desert dust (DD) is associated with AOD > 0.6 and $\alpha < 1.0$, while AOD < 0.2 and $\alpha > 0.5$ correspond to clean conditions (CC). Biomass burning (BB) is detected with AOD > 0.8 and associated $\alpha > 1.0$. The case with AOD in the range of 0.3–0.8 associated with $\alpha > 1.0$ corresponds to anthropogenic aerosols (AA), while AOD and associated $\alpha$ in the range of 0.2–0.6 and 0.4–1.0 respectively, correspond to mixed aerosols (MA). It is quite difficult to discriminate the well-mixed aerosol types.

Fig. 5 describes a scatter plot of AOD$_{500}$ Versus $\alpha_{440-870}$ for DDN on a monthly basis and associated five aerosol classes as per above. It is easy to identify the high loading of DD with high AOD and low $\alpha$ over DDN during May. The contamination of BB with high AOD and $\alpha$ is observed to be very less during this study. Cases related to low AOD and high $\alpha$ characteristic of AA discriminated. The high-density area of associated low AOD and low $\alpha$ can mostly dominate by MA due to various atmospheric processes. The dominance of AA and MA is found in all seasons.

Fig. 6 describes the percentage contribution of four different aerosol types (MA, AA, DD and BB) over DDN during pre-monsoon season. The high dominance of MA has been detected during March, April and June (56.67%, 51.27% and 47.13%), whereas DD contributes 55.66% during May that indicates the high loading of desert dust in

Fig. 3. Monthly mean spectral AOD distribution over DDN during pre-monsoon season 2012.
the atmosphere over DDN due to frequent dust events. The involvement of AA in the range of 17%–37% in all seasons depicts the pollution of the area. The tourist movement in DDN causes the pollution in the area through exceeding the fuel combustion in vehicles. With this, the diurnal cycles of atmospheric boundary layers invoke the air with aerosols to high altitudes (DDN) from polluted areas. The contribution of BB is found to be very small, ranging from 1%–6% during pre-monsoons season over DDN. Kaskaoutis et al. (2007) suggested the correlation between AOD and $\alpha$ was found to be neutral. It suggests the various sources of seasonally dependent aerosols, which will be revealed by seven-day back trajectories in this paper.

Seven-day back trajectory analysis has been carried out using Hybrid Single-Particle Lagrangian Integrated Trajectory (HY-SPLIT) model of the National Oceanic and Atmospheric Administration (NOAA), United States (http://www.arl.noaa.gov/ready/hysplit4.html) to study the transportation of dust particles over DDN during dust events. Fig. 7 illustrates the seven-day air-mass back trajectories along with a variation of relative humidity at 500 m (mixed layer), 1500 m (above the boundary layer where convection causes the elevation of dust) and 2500 m (in the free troposphere) for an individual month during pre-monsoon over DDN. This analysis has shown that the dust originates from three different sources, namely the Thar Desert in Rajasthan, Southwest Asia (Iran, Pakistan) and Oman. The air masses with average relative humidity (40%–50%) during May (especially during dust events) are passing over the Thar Desert before approaching to the station (DDN). On the other side, long-range transportation of dust with low relative humidity (20%–30%) at a high degree of altitudes also contributes to the high AOD during May. During the end of the season (June), air masses approaching from the Arabian ocean lead to increase the amount of relative humidity (70%–80%), which help to particles for the hygroscopic growth.

Fig. 4. Monthly summary of (a) AOD500 and (b) Angstrom exponent in box charts over study region.

Fig. 5. Scatter plot of the AOD500 versus Angstrom exponent for the discrimination of different aerosol types over Dehradun.
Fig. 6. Contribution of each aerosol types in percentage to the total in each month over DDN during premonsoon season (MA = mixed aerosol, DD = desert dust, AA = anthropogenic aerosol, BB = biomass burning).

Fig. 7. Seven-day back trajectories over study region along with variation of relative humidity using HYSPLIT model.

**OPAC Derived Volume Size Distribution and Optical Properties**

OPAC simulations were performed to estimate the aerosol properties e.g., volume size distribution, single scattering albedo and asymmetry parameter in order to estimate the direct shortwave radiative forcing over DDN.

Fig. 8 describes the estimated monthly mean volume size distribution (dV/dlogr) using OPAC model over DDN.
for pre-monsoon season. The results reveal the trend of bimodal structure in size distribution. The parameter of the volume size distribution is given in Table 2. The monthly mean volume concentration of fine mode and coarse mode are found to be within the range of 3.42–4.53 and 5.35–15.56 respectively. The volume concentration of coarse particles is found to be increased without much change in the radius due to frequent dust events during May. The monthly mean radius varies within the range of 0.153–0.168 for fine particles and 2.853–2.919 for coarse particles. SSA and g are retrieved along with volume size distribution using an OPAC model for the spectral range 0.4–0.9 µm, which are described in Figs. 9(a) and (b). SSA values are observed to be strongly wavelength dependent. SSA increase with wavelength during dust period and shows the reverse trend during non-dust period. The loading of urban polluted aerosols is dominant during March, April and June over DDN (easily, we can see in the volume size distribution (Fig. 8)), which shows lower SSA at longer wavelengths. The SSA is found to be increased with

![Graph 8](image1.png)

**Fig. 8.** OPAC simulated monthly mean aerosol volume size distribution over DDN.

### Table 2. Simulated monthly mean volume size distribution parameters of aerosol particles using OPAC model.

<table>
<thead>
<tr>
<th>Type of Particles</th>
<th>Parameters</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine Mode</td>
<td>V</td>
<td>4.53</td>
<td>4.24</td>
<td>3.42</td>
<td>4.01</td>
</tr>
<tr>
<td></td>
<td>R&lt;sub&gt;V&lt;/sub&gt;</td>
<td>0.153</td>
<td>0.159</td>
<td>0.168</td>
<td>0.159</td>
</tr>
<tr>
<td>Coarse Mode</td>
<td>V</td>
<td>5.35</td>
<td>10.47</td>
<td>15.56</td>
<td>9.18</td>
</tr>
<tr>
<td></td>
<td>R&lt;sub&gt;V&lt;/sub&gt;</td>
<td>2.853</td>
<td>2.899</td>
<td>2.919</td>
<td>2.89</td>
</tr>
</tbody>
</table>

<sup>1</sup>V is the volume concentration (µm³ cm⁻³) and R<sub>V</sub> (µm) is the volume geometric mean radius.

![Graph 9a](image2.png) ![Graph 9b](image3.png)

**Fig. 9.** Single scattering albedo and asymmetry parameter derived from OPAC model for the spectral range 0.4–0.9 µm over DDN.
wavelength during May indicating the dominance of coarse particles through frequent dust events (Ackerman and Toon, 1981). The estimated value of SSA (~0.92) suggests the more scattering in the atmosphere due to loading of coarse particles. The estimated SSA value over DDN supports the study of Moorthy et al. (2007). He was reported that the SSA values of dust over India lie between 0.88 and 0.94 that indicates the dust over Great Indian Desert is more absorbing compared to African Dust. Similar to this, Fig. 9(b) describes the spectral variation of an asymmetry factor (g) during pre-monsoon. The spectral variation of g is a representation of the angular scattering and depends on the size and composition of the particles. It is an important property controlling the aerosol contribution to forcing, which varies between −1 (entirely backscattered light) and +1 (entirely forward scattered light). The value of g is found to be decreased in visible and near infrared region during non-dust period, whereas g is increased in the near infrared region due to forward scattering suggesting the loading of coarse mode particles during dust period (May).

**Aerosol Direct Radiative Forcing**

The estimated daily ARF is averaged on a monthly basis, which is illustrated in Fig. 10. ARF at the surface is always negative due to the attenuation of solar radiation at the surface by aerosols. A negative forcing at the TOA indicates the enhancement in backscattering by scattering aerosols leading to cool the atmosphere and Earth system, whereas a positive forcing by absorbing aerosols contributing to warming the atmosphere. The difference between TOA and surface radiative forcing introduces the atmospheric radiative forcing.

The estimated surface and TOA shortwave radiative forcing are found to be negative in the premonsoon season, which varies between −4.84 ± 0.96 and −14.49 ± 2.89 W m⁻² for surface and −24.65 ± 4.93 and −53.29 ± −8.45 W m⁻² for TOA. The surface ARF is found to be maximum (−53.29 ± 8.45 W m⁻²) in May over DDN. Similarly, the ARF at TOA is found to be high (−14.49 ± 2.89 W m⁻²) during May, which indicates the scattering of solar radiation due to frequent dust events over DDN. The loading of dust aerosols leads to maximum positive atmospheric radiative forcing (38.79 ± 8.35 W m⁻²) during May. Table 3 describes the comparison of radiative forcing over DDN with other regions of northern India, it is seen that the magnitude of TOA forcing is more or less comparable at all the locations except at Kanpur (Dey et al., 2006) and Delhi (Pandithurai et al., 2008). Dey et al. (2006) reported the positive TOA ARF during dusty days in May 2004, whereas, Pandithurai et al. (2006), have reported positive TOA ARF especially during May and June, 2006.

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**Fig. 10.** Estimation of monthly mean aerosol radiative forcing at top of atmosphere (TOA), surface and within the atmosphere over DDN during premonsoon season 2012.

**Table 3.** Comparison of aerosol radiative forcing estimated over DDN with those reported from other locations in Northern India during Pre-monsoon.

<table>
<thead>
<tr>
<th>Locations</th>
<th>References</th>
<th>TOA (W m⁻²)</th>
<th>Surface (W m⁻²)</th>
<th>Atmosphere (W m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dehradun (DDN)</td>
<td>Present Study</td>
<td>−9.93 ± 1.9</td>
<td>−40.78 ± 6.1</td>
<td>30.85 ± 6.4</td>
</tr>
<tr>
<td>Dibrugarh</td>
<td>Pathak et al. (2010)</td>
<td>−1.4 ± 2.9</td>
<td>−37.1 ± 8.7</td>
<td>35.7 ± 6.4</td>
</tr>
<tr>
<td>Kanpur</td>
<td>* Prasad et al. (2007)</td>
<td>−13.5</td>
<td>−57.5</td>
<td>−</td>
</tr>
<tr>
<td>Kanpur</td>
<td>* Dey et al. (2006)</td>
<td>11 ± 0.7</td>
<td>−26 ± 3</td>
<td>36 ± 4</td>
</tr>
<tr>
<td>Delhi</td>
<td>* Pandithurai et al. (2008)</td>
<td>3.25</td>
<td>−77</td>
<td>79.5</td>
</tr>
</tbody>
</table>

* Study performed particularly for dusty days only.
# The mean values are consider here for the Delhi, which was observed individually month wise by Pandithurai et al. (2006) during pre-monsoon.
The estimated mean surface and TOA forcing efficiency (−73.1 and −19.8 W m$^{-2}$ per unit AOD at 500 nm, respectively) indicate the scattering nature of aerosols during May over station, which is quite comparable to other previous studies at other locations in northern India during dusty days. Gautam et al. (2010) reported large negative surface forcing efficiency −70 W m$^{-2}$ τ$^{-1}$ during dust events over IGP depicting high absorption of solar radiation at the surface. Sharma et al. (2012) have reported mean surface and TOA forcing efficiency −66.64 W m$^{-2}$ τ$^{-1}$ and −14.5 W m$^{-2}$ τ$^{-1}$ during dust over Patiala. Similarly, the large values of surface forcing efficiency were found to be −71, −85, −87 and −84 W m$^{-2}$ τ$^{-1}$ for March, April, May and June 2006, respectively by Pandithurai et al. (2008) over Delhi. The dust events lead to the enhancement of heating rate in the atmosphere during May. The monthly mean heating rate in the lower atmosphere is 1.06° K d$^{-1}$ for May over DDN, which is slightly more than the heating rate (−1.02° K d$^{-1}$) obtained by Dey et al. (2006) over Kanpur. Higher values of heating rates can have an impact on monsoon circulation and regional climate system (Ramanathan et al., 2007). The details of radiative forcing, forcing efficiency and heating rates for individual months is given in Table 4. The study of influences of enhanced aerosol heating during pre-monsoon and their impacts are required.

CONCLUSIONS

Dust impacts on aerosol properties were examined in the present study over Dehradun, in the northwestern part of India, by ground measurements and satellite remote sensing. The major results are summarized as follows.

- Dehradun is characterized by high aerosol optical depth at 500 nm during pre-monsoon season. The mainly local diurnal variation controlled the AOD spectrum, but the dust events in May have a strong influence on the AOD spectrum. The AOD values up to 1.05 have been observed during dusty days. The AOD spectrum is found to be decreased by the rise at the longer wavelength. This is reflected to low values by α (< 0.25), attributed to the abundance of coarse particles due to frequent dust events, which are justified by MODIS and OMI observations over DDN. The six intense dust events have been identified in the May 2012.

- The daily observations of aerosol were used for discrimination of the aerosol types by the scatter plot between AOD and α on a monthly basis. The aerosol type analysis revealed loading of dust aerosol (> 55%) during May and dominance of mixed aerosols (> 47%) during other months of pre-monsoon. The dust transported from the western region has been analyzed by seven-day back trajectory.

- The dust events introduce a large increment in the volume concentration at the coarse mode and small decrement in the volume concentrations at the fine mode. The OPAC simulated values of SSA (> 0.90) are increased at longer wavelengths suggesting the loading of coarse particles over DDN, which was supported by the simulation of g values.

<table>
<thead>
<tr>
<th>Months</th>
<th>Radiative Forcing (W m$^{-2}$)</th>
<th>Aerosol Optical Depth</th>
<th>Atmospheric Heating Rate (K d$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>March</td>
<td>−4.84 ± 0.96</td>
<td>0.306</td>
<td>−15.82 ± 3.36</td>
</tr>
<tr>
<td>April</td>
<td>−8.87 ± 1.77</td>
<td>0.411</td>
<td>−21.60 ± 4.32</td>
</tr>
<tr>
<td>May</td>
<td>−14.49 ± 2.89</td>
<td>0.729</td>
<td>−19.87 ± 3.97</td>
</tr>
<tr>
<td>June</td>
<td>−11.52 ± 2.30</td>
<td>0.475</td>
<td>−24.26 ± 4.85</td>
</tr>
</tbody>
</table>
• The estimated ARF shows an increment during May compared to other months during pre-monsoon. The mean ARF values at the surface and TOA are ~53.29 W m$^{-2}$ and ~14.49 W m$^{-2}$ respectively during May. The increment in net atmospheric forcing (38.79 W m$^{-2}$) corresponds to increase at a heating rate of ~1.06° K d$^{-1}$ in the lower atmosphere.

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2093