Analysis of Aerosol optical Characteristics and Radiative effect over Northwest Himalayan region

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ABSTRACT

The study examined the variability of aerosol optical properties and radiative effects over northwest Himalayan region using synergy of ground-based and satellite observations. The spectral aerosol optical depth (AOD) measurement was carried out by using Microtops Sunphotometer and MODIS&MISR over Dehradun, part of Northwest Himalayas during January-December 2015. It is observed that during pre-monsoon, region experiences high mean AOD_{500} (0.34±0.09 to 0.63±0.12) alongwith low mean Ångström exponent (α) (0.46±0.09 to 0.66±0.10) attributing to the dominance of mineral dust aerosols while moderate mean AOD_{500} and moderate α during monsoon and post monsoon season are (0.38±0.08 to 0.54±0.16) and (0.78±0.1 to 0.91±0.11) respectively indicating mixed type aerosols. During winter, low mean AOD_{500} (0.29±0.06 to 0.46±0.12) and high mean α (1.12±0.09 to 1.30±0.1) is observed due to domination of fine mode aerosols coming from anthropogenic activities. The frequency distribution of AOD (500 nm) is found to be maximum (0.3) in all seasons except monsoon (0.6). Comparison of satellite derived AOD agrees well with ground based Microtops (MT) measurements (R=0.80 and 0.71 for MODIS and MISR respectively) over Dehradun. Classification of aerosol types reveals that MA (Mixed Aerosol) type is dominated in almost all seasons over the region. The SBDART model was used to estimate the Aerosol Radiative forcing (ARF) at the Surface (SUR), the top-of-atmosphere (TOA) and Atmosphere (ATM). The annual mean ARF at SUR, TOA and ATM are −42 W m^{-2},-16 W m^{-2}, and +25 W m^{-2} respectively. The ratio of surface to TOA ARF is found to be ~2.6 indicates the dominance of absorbing aerosols over the region.

I. INTRODUCTION

Atmospheric aerosols are play a major role in uncertainty of climatic radiative forcing by directly scattering and absorption of solar incoming radiation and by indirectly altering cloud microphysical properties (Satheesh and Krishna Moorthy 2005). The magnitude and variability of the uncertainty depends on the distinct characteristics and size distributions of aerosols and are also responsible for impact on air quality and human health Important Parameters like spectral aerosol optical depth (AOD), water vapor content, ozone, asymmetry parameter (g), surface albedo, single scattering albedo (SSA), and vertical distribution of aerosols helps in understanding & observing radiated effects. The Aerosol Radiative Forcing is the change in the net, downward minus upward, irradiance (Wm^{-2}) either at the surface or top of the atmosphere with and without aerosols in the atmosphere. The attention on aerosol properties and effect on radiative forcing over India is found to be increasing and a regular spectral aerosol measurements on studying optical & radiative Properties are being carried out at a number of locations under the Indian Space Research Organization (ISRO), Geosphere – Biosphere programme. This program initiated Aerosol Radiative Forcing over India (ARFI) network which involves continuous aerosol measurements at various locations (42 stations) to assess the aerosol radiative forcing over India (Moorthy 1989). As a major aspect of this programme, continuous aerosol measurements are being carried out at Dehradun station for measurements over a part of North West Himalayan region. The paper presents the monthly and seasonal variation of aerosol optical properties and radiative forcing over the Northwest Himalaya during 2015.

II. SITE DESCRIPTION

The observational site is situated at Indian Institute of Remote Sensing (ISRO), Dehradun (30.30 0N, 78.03 0E, 700 amsl). Dehradun is the capital city of Uttarakhand state and located in the North West of Himalayan region, adjacent to foothills of Himalayas. Dehradun is a semi-urban metropolitan city surrounded by Siwalik Hills in south and Himalayas in North, while it is open in Northwest and southeast. Thar Desert (source of Desert dust) and Delhi (source of anthropogenic emission city) are located in southwest of the observational site (see Fig. 1). There is no major industries and roads in nearby the observational site, therefore there is no immediate effect on the sampling collections. However, local vehicular emissions, seasonal dust events, long range transport from other regions and biomass burning activities are the major possible sources of aerosol loading over the region. Based on regional climatology, the region experiences four dominant seasons in each year, winter (December–February), pre-monsoon (March –June), monsoon (July–September) and post-monsoon (October–November). During the pre-monsoon season, air mass carries dust particles by North westerly winds from Thar Desert and western regions and during post monsoon season, the winds from Northwestern IGP region brings large scale black carbon and other fine particles due to biomass burning and agricultural crop residue burning (Kant et al. 2012). During winter, the region experiences calm winds and dense fog/haze conditions due to low temperatures, higher relative humidity (RH) and trapping of pollutants near ground.

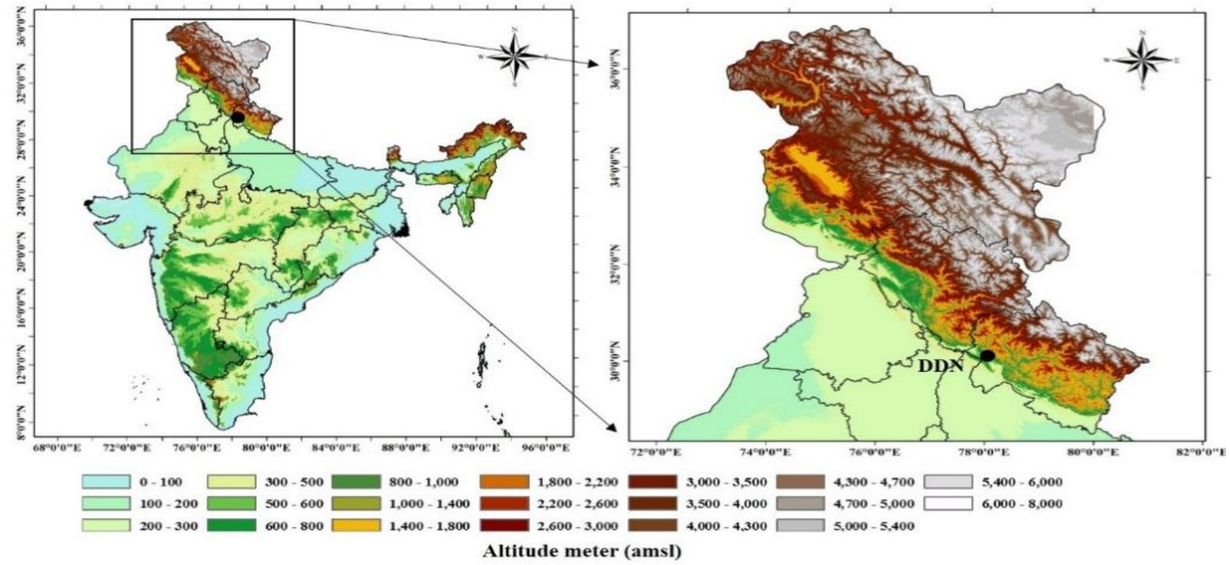

Fig. 1. *Topography map of India and Northwest Himalayan region.*

III. DATASETS AND INSTRUMENTS

A. Microtops II

The AOD measurements were carried out using a set of Microtops-II sunphotometers (MT) (Solar Light Co., USA) with extended seven wavelengths from 380-1020 nm. For internal calibrations, the Langley method was used and the Full Width at Half Maximum (FWHM) bandwidth of the channels are 2.4 ± 0.4 nm to 10 ± 1.5. The cumulative error in the AOD measurements due to Rayleigh scattering and molecular absorption is found to be 2-5% for the MT sunphotometer at different wavelengths (More et al. 2013). The Sunphotometer observations were taken every one hour during the day time from 09:00 to 17:00 h local time on all cloud free days. The daily AOD data utilized to retrieve the Angstromexponent, which is an index of aerosol size distribution. For inter-comparison purpose, satellite retrievals must be collocated in space and time with Microtops measurements.

B. MODIS

Moderate Resolution Imaging Spectrometer (MODIS) on-board Terra and Aqua provides daily global data of aerosol properties measuring sunlight reflected by earth's atmosphere & surface and emitted thermal radiation at 36 wavelengths. There are two different algorithms to retrieve aerosol properties over land and over ocean. The land algorithm for MODIS data is an inversion, but it takes only three nearly independent observations of spectral reflectance (0.47, 0.66 and 2.1 mm) to retrieve three nearly independent pieces of information. These include total AOT at 0.55 mm, fine (model) weighting at 0.55 mm, and the surface reflectance at 2.1 mm. MODIS Terra and Aqua derived aerosol products are tested, validated and being used to investigate spatiotemporal variations in aerosol optical characteristics(Levy et al. 2010),(Remer et al. 2008). In the present study, Level 2 MODIS Collection6 atmosphere daily global AOD was utilized. Daily aerosol optical depth at 550 nm from January –December 2015 was downloaded and processed over the Dehradun region and further Monthly mean AODs were generated.

C. MISR

Multi-angle Imaging Spectroradiometer (MISR), on-board the NASA Earth Observing System's Terra satellite, it consist of 9 cameras that view the Earth surface in nine different angles (4 forward, 4 backward and 1 nadir) ranging from 70◦ backward to 70◦ forward at four different wavelengths i.e. 446, 558, 672 and 866 nm. The instrument scans the Earth surface in 360 km swath resolution that requires about 9 days to complete global coverage. For the advantages of multi-wavelength and multi-angle radiance observations it provides the ability to discriminate spherical and nonspherical aerosols in 17.6× 17.6 km spatial resolution. The MISR level 3 aerosol product has been extensively evaluated over the Indian subcontinent (Bibi et al. 2015). Daily MISR Level 3 (0.5° × 0.5° resolution) Component Global Aerosol Product is used for the present study.

D. OPAC

Optical properties of aerosol particles suspended in the atmosphere depend upon their chemical composition, size, shape, mixing state and concentration. The Aerosol optical properties such as AOD, angstrom exponent, single scattering albedo (SSA) and the asymmetry parameter (g) are critical to the estimation of aerosol radiative forcing, for which SSA plays a major role(Singh et al. 2010). Due to lack of required aerosol parameter measurements (SSA and g) over the region, Optical Properties of Aerosol and Clouds (OPAC) model (Hess, Koepke, and Schult 1998) was used to derive the optical properties of aerosols. Keeping in view of the composition of aerosols over the observational site, five different aerosol types viz., soot, water soluble, insoluble, mineral accumulation and mineral transport as externally mixed particles forming the composite aerosols were fixed in the OPAC model. Angstrom exponent was calculated from spectral information from ground measured AOD while SSA and asymmetric parameter were simulated using OPAC model. The AOD values thus obtained from the OPAC model on all days were compared with the observed AOD with RMS deviation less than 5%.

E. SBDART

Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART) model is a simple plane-parallel radiative transfer model based on the discrete ordinated approach, developed by the University of California (Ricchiazzi et al. 1998) for estimating the aerosol radiative forcing for both clear sky and cloudy conditions. SBDART is a well-calibrated code for estimation of radiative flux and has been satisfactorily used over Indian region (Aruna et al. 2016).Various aerosol optical parameters simulated from OPC – spectral AOD, single scattering albedo (SSA), asymmetry parameter (g) are used as input to SBDART model and other essential inputs are model atmosphere & surface albedo. Based upon the measured aerosol parameters and the prevailing weather conditions over Northwest Himalayan region, the mid-latitude summer atmospheric profile has been selected. In the present study, AOD, Angstrom exponent (α), SSA, g and actual albedo were used as an input to SBDART for computing Aerosol radiation forcing (ARF) at the surface (SUR) at the top of the atmosphere (TOA) and Atmosphere (ATM) associated without and with aerosol conditions using below equation (Babu 2002),

$$Aerosol\ Radiative\ forcing\ (ARF) = (\Delta F)_{without\ aerosol} - (\Delta F)_{aerosol} \quad (1)$$

Where ΔF is net radiative flux (Downward flux– Upward flux). The value of ARF represents the quantity of energy trapped within the atmosphere due to the presence of aerosols. The uncertainties in SBDART ARF calculations arise mainly from various assumptions such as model atmosphere and OPAC simulations. The overall uncertainty in SBDART estimation is within the range of 20% (Kumar et al. 2011).

IV. RESULTS AND DISCUSSION

A. Variation of AOD and Angstrom Exponent

The aerosol optical depths were measured at six wavelengths 380, 440, 500, 675, 870 and 1020 nm during clear-sky conditions and corresponding angstrom exponent α (380 nm – 870 nm) were derived using Angstrom power law,

$$\tau(\lambda) = \beta(\lambda)^{-\alpha} \quad (2)$$

Where τ(λ) spectral variation of AOD, β is turbidity constant which is equal to the AOD measured at 1 μm and α is the angstrom exponent. Angstrom exponent is a rough representation of the size distribution of columnar aerosols. The spectral dependence of the AOD as well as the Ångström exponent are sensitive to the calibration coefficients. Basic categorization of Angstrom exponent(α) values, greater than 2.0 indicate fine–mode particles while values of near zero indicate the presence of coarse–mode particles such as desert dust (Eck et al. 1999). Fig. 2 shows daily and monthly averaged values of AOD at 500 nm and α (380–870 nm) for January to December 2015, with error bars showing the standard deviation of the monthly averaged value. A close monthly analogy show a large scatter in both parameters due to large variability in local synoptic conditions, boundary-layer dynamics and long-range transport. The annual mean AOD at 500 nm during the period of present observations is ~0.40±0.13 with an average Angstrom exponent ~1.10±0.21 while the daily averaged values range from as low as ~0.12 to as high as ~1.22 and ~0.22 to ~1.60, AOD_{500} and α respectively. Throughout the year, the maximum value occurred in May (0.63±0.27) while the average monthly Angstrom exponent values during this month were 0.91±0.22, indicating that the windblown dust enhances. On the other hand the minimum monthly mean AOD was observed during March (0.34±0.19) and July (0.39±0.14) with the mean α values being 1.01±0.19 and 1.26±0.23, respectively due to seasonal rains occurring during these months.

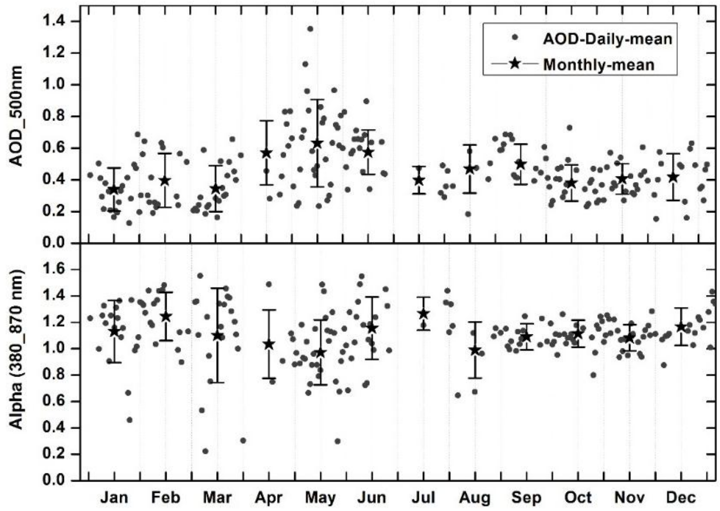

Fig. 2. *Time series of the daily averaged AOD_{500} and Alpha over Dehradun during 2015*

B. Frequency Distribution of AOD

Seasonal frequency distribution of AOD_{500} is shown in Fig. 3. In order to accommodate the wide range of aerosol characteristics encountered over Dehradun, AOD values are segregated into seven bins in the range of 0.0-0.2, 0.2-0.4, 0.4-0.6, 0.6-0.8, 0.8-1.0, 1.0-1.2 and 1.2-1.4. Large variability in the AOD values are observed in each season since a narrow segregation bin are chosen for obtaining seasonal dependence of aerosol characteristics. During the winter, 76% of the AODs were observed between 0.2 – 0.6 and 13% of the AODs ranged below 0.2. The widest frequency distribution occurred in the pre-monsoon were 61% of the AODs observed between 0.2 – 0.6, 36% are in range of 0.8-1.4 and 3% are in below 0.2. In monsoon and post-monsoon seasons, AODs are nearly 69% and 78% of occurrences in range of 0.2 – 0.6. However, during post monsoon season only three peaks are seen in lower AOD bins (see Fig. 3) illustrating anthropogenic aerosol emission sources during this season. The Gaussian model was used to fit the frequency distributions (solid lines in Fig. 3) for four individual seasons. The equation of the Gaussian model is

$$y = y_0 + \left(\frac{A}{w\sqrt{\pi/2}} \right) \times \exp\left(\frac{-2\left(x - x_C\right)^2}{w^2} \right) \quad (4)$$

Where A is the amplitude, Xc is the center of the peak amplitude, and ω is the width at half peak amplitude. The seasonal statistics of the AODs based on the fitted Gaussian model is summarized in table. 1.

Table.1. *Seasonal Statistics of the AOD Based on the Fitted Gaussian Model.*

Seasons	Y_0	X_C	W	A	R^2
Winter	-0.170 ±0.29	0.379 ±0.002	0.358 ±0.005	20.502 ±0.343	0.99
Pre monsoon	1.462 ±6.908	0.456 ±0.068	0.483 ±0.192	18.430 ±9.457	0.57
Monsoon	0.588 ±0.522	0.517 ±0.004	0.309 ±0.007	19.180 ±0.550	0.99
Post monsoon	0.283 ±3.213	0.395 ±0.016	0.273 ±0.060	19.623 ±3.449	0.93

The normal probability function best represents the frequency distributions (Zheng et al. 2008),(Pawar, Devara, and Aher 2015), the correlation coefficients are 0.99 (winter), 0.57 (Pre-monsoon), 0.99 (monsoon) and 0.93 (Post-monsoon). During pre-monsoon season, the correlation coefficient is quite low than that from other seasons due to wide range of AOD distributions due to influence of mineral dust.

C. Comparison of Ground measured and Satellite derived AOD

Inter Comparisons between satellite derived and ground measured AOD are essential for estimating uncertainties in satellite observations, for data assimilation and for the development of improved retrieval algorithms. MODIS and

MISR AODs are broadly able to capture the seasonal variations i.e. low AOD values during winter and high during pre-monsoon. However, the magnitudes of AODs are found to exhibit distinct behavior in each month. The satellite measurements shows that the monthly mean MODIS and MISR AOD values ranged from 0.05 to 1.02 and 0.06 to 0.47 respectively whereas the ground based measurements ranged from 0.21 to 0.62. The linear regression parameters such as slope and intercept are assumed to be the highest importance in validation studies (More et al. 2013).

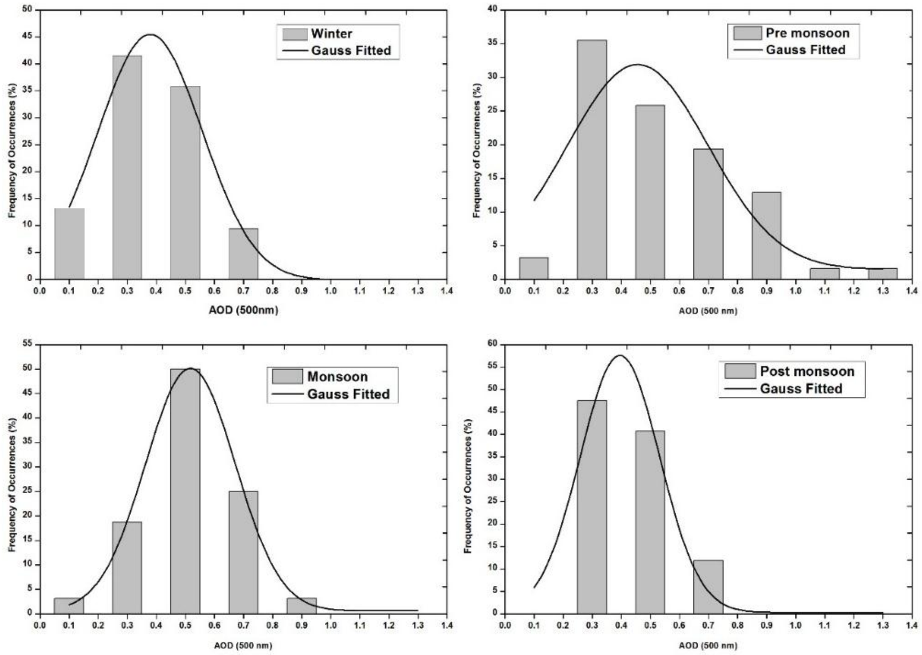

Fig. 3. *Frequency distributions of the AOD (500 nm) for the four seasons and the fitted Gaussian model.*

A one-to-one correlation between MT AOD and satellite AODs (MODIS and MISR) during 2015 as depicted in Fig. 4. The MODIS AOD retrievals corroborate well with the MT measurements with a correlation coefficient of 0.80 with corresponding slope and intercept as 0.82 and 0.01 respectively whereas for MISR correlation coefficient, slope and intercept are 0.71, 0.65 and 0.02 respectively. The MT AOD shows strong correlation with MODIS AOD as comparison to that with MISR. This may be due to less number of available MISR data over the region.

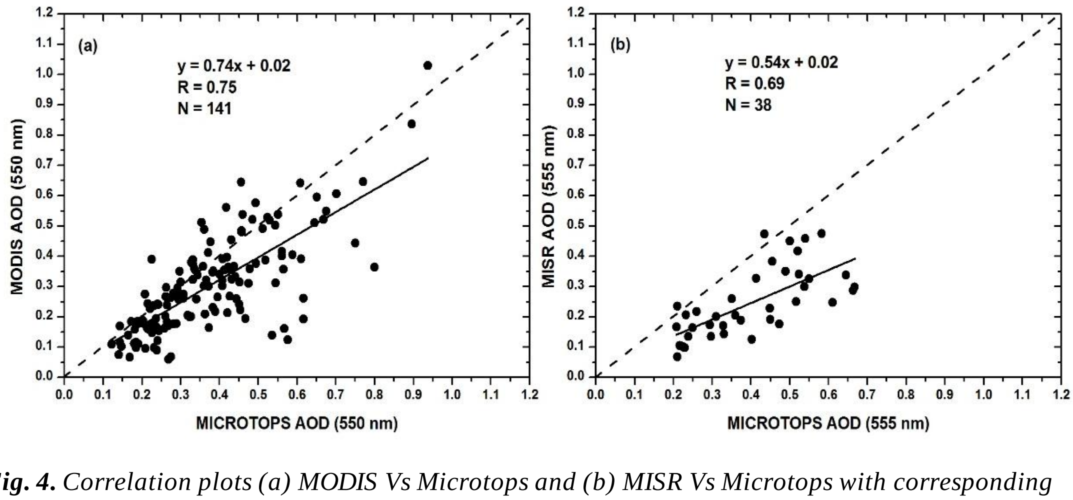

Fig. 4. *Correlation plots (a) MODIS Vs Microtops and (b) MISR Vs Microtops with corresponding wavelengths over Dehradun during 2015.*

D. Domination of Aerosol Types

Microtops and satellite measurements shows a significant divergence in aerosol loading over Dehradun with significant seasonal changes. Divergence in aerosol loading and aerosol types are due to varied sources, emission and transport mechanisms. Classification of aerosol types is generally attained by means of scatter plot between aerosol loading (AOD) and aerosol size (α). This method is widely used by several investigators (Kalapureddy et al. 2009),(Patel and Kumar 2015) and suggesting that Indian subcontinent contributed into five main aerosol types such as continental average (CA), marine continental average (MCA), urban/industrial and biomass burning (UI/B), desert dust (DD) and the remaining cases as indeterminate or mixed type (MT). The majority of the above cases a well-mixed aerosol type occurs, which is rather difficult to be classified (Holben, B.N., D.Tanre, A.Smirnow, T.F.Eck, I.Slutsker, N.Abuhassan, W.W.Newcomb, J.S.Schafer, B. Chatenet, F.Lavenu, Y.J. Kaufman, J. Vande Castle, A.Setzer, B.Markham, D.Clark, R.Halthore, A. Karneli, N.T. O'Neili, C.Pietras, R.T.Pinker 2001). For the aerosol type determination, the thresholds values of AOD and α levels have been utilised suggested by (Kaskaoutis et al. 2009).

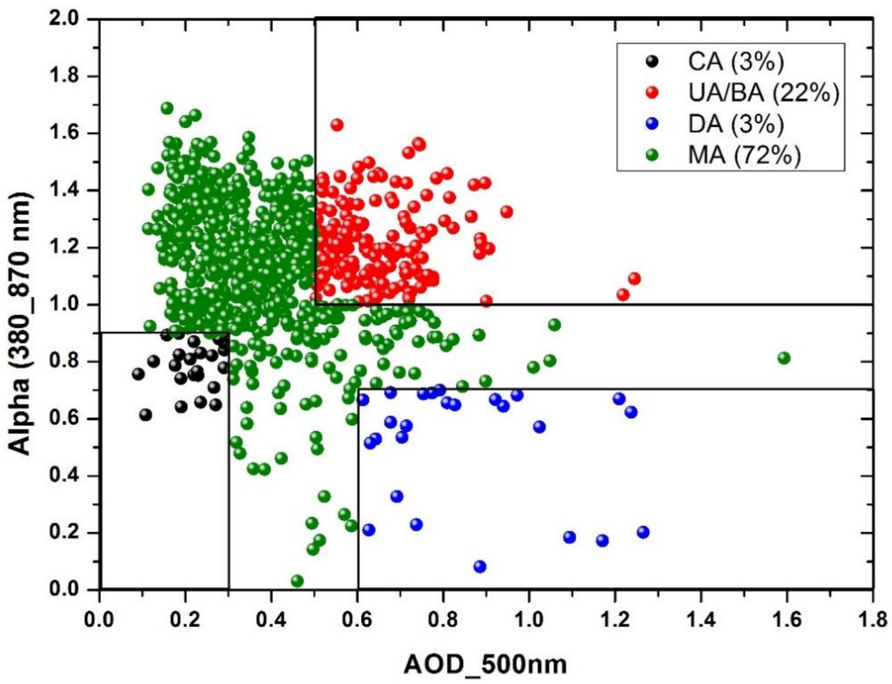

Fig. 5. *Scatter plot between AOD_{550} and Angstrom exponent (380–870 nm) for the discrimination of different aerosol types.*

Fig. 5 depicts the scatter plot of AOD500 nm against α (380_870nm) during 2015. Percentage of contribution through year for CA, UA, DA and MA are 3%, 22%, 3% and 72% respectively. The absolute maximum contribution was observed aerosol types belongs to the MA category *i.e.* 72% over the Northwest Himalayas. The analysis reveals that the UA/BA clearly dominates in monsoon (58%) and some fraction *i.e.* 22%, 20% during winter, post monsoon seasons respectively while the DA type exhibits its highest presence during pre-monsoon *i.e.* 8% and more rarely *i.e.* 2% during monsoon and nearly absent during the rest of the year. In all seasons, majority of contribution is not belonging to any of the above aerosol type's *i.e.* MA was found. The dominance of mixed type aerosols may be due to the coarse-mode particles are mixed with local pollution or with smoke biomass burning (Pawar et al. 2015), is not an easy task to qualitatively and quantitatively segregation of MA type due to different land use, environmental characteristics and limited observations.

E. Aerosol Direct Radiative Forcing

Using the SBDART model with the required inputs as detailed above (see section), down welling and upwelling radiative fluxes in the wavelength range of 0.25–4.0 μm at the TOA, SUR and ATM have been estimated. ARF values depend strongly on the scattering and absorbing nature aerosols, which are governed by their size distribution and chemical composition (Sinha et al. 2013). Fig. 6 shows the average monthly variation in ARF along with the standard deviations obtained over Dehradun. The average forcing for the whole period of observations at the surface was of the order of −42 Wm^{-2}, at the top of the atmosphere around -16 W m^{-2}, giving rise to an atmospheric forcing about +25 Wm^{-2}. The ARF maximum values were observed in May at SUR, TOA and ATM are −57±23 Wm^{-2}, −20.68 W m^{-2} and 36.64 Wm^{-2} while in minimum values observed in Jan, -30.54 Wm^{-2}, -11.14 W $m^{-2}$and 19.40 Wm^{-2} respectively. Higher surface aerosol forcing in May is due to the higher aerosol loading (the AOD is 0.63 at 500 nm). In comparison the ARF surface values high during Pre-monsoon (32 Wm^{-2}) and low (21 Wm^{-2}) during winter, where as in the Post-monsoon (25 Wm^{-2}) and monsoon (22 Wm^{-2}) the atmospheric forcing is stagnant.

V. CONCLUSIONS

The daily and monthly mean variations of the aerosol optical properties and radiative forcing were studied over North-west Himalayan region during the year 2015 using ground measurements and satellite remote sensing data sets. The major results are summarized as follows.

- The AOD and Alpha at this location varies with season and is mainly influenced by weather conditions, dust events, human activities and local topography. The annual average AOD at 500 nm during the period of present observations is ~0.45±0.32 with an average Angstrom exponent ~1.10±0.15. Spectral dependence of AOD showed higher values at shorter wavelengths which decreases gradually towards longer wavelengths for throughout year suggesting anthropogenic aerosols contribute substantially to AOD over the region.

- The seasonal variation of the frequency distribution indicates distinct source of aerosols loading over the region. The large variation of the AOD values in the range 0.1 to 1.4 was observed in summer while 0.1 to 0.9 for rest of seasons. A Gaussian normal distribution best characterized the frequency distribution of AOD for each season.

- Inter-comparison of MODIS and MISR derived AODs with respect to Microtops measured AOD are found to be in good agreement.

- The Aerosol types were mainly dominated by mixed type (72%), Urban/Biomass type (22%), Dust type (3%) and Clean Conditions (3%) through the year.

- The monthly variation of AOD is significantly affect the ARF over the Northwest Himalayan region. The monthly average ARF at SUR varied in the range −30 Wm^{-2} to −57 Wm^{-2} and at TOA in the range −11 Wm^{-2} to -21 Wm^{-2} and ATM in the range +19 Wm^{-2} to +36 Wm^{-2}.

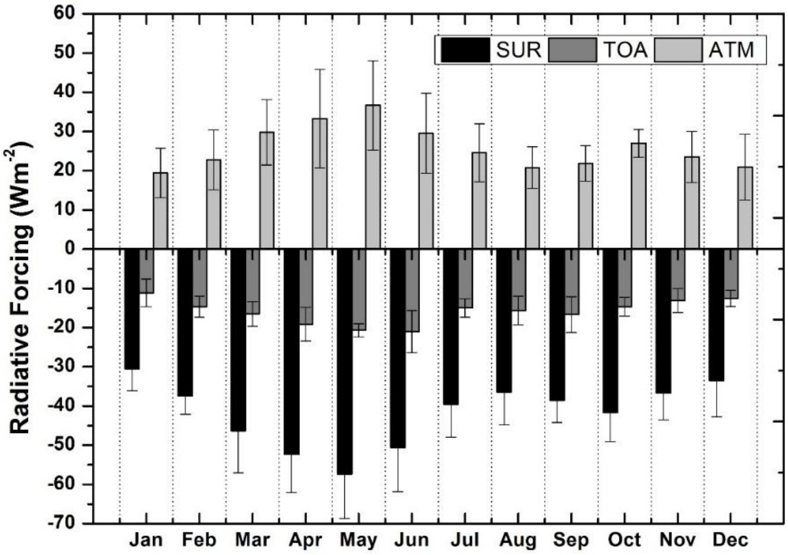

Fig. 6. *Variation of monthly mean Aerosol Radiative Forcing (ARF) at surface, top of the atmosphere and in the atmosphere during 2015 over Dehradun.*

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REFERENCES

Aruna, K. et al. 2016. "Short Wave Aerosol Radiative Forcing Estimates over a Semi Urban Coastal Environment in South-East India and Validation with Surface Flux Measurements." *Atmospheric Environment* 125:418–28.

Babu, S. Suresh. 2002. "Aerosol Radiative Forcing due to Enhanced Black Carbon at an Urban Site in India." *Geophysical Research Letters* 29(18):1–4.

Bibi, Humera et al. 2015. "Intercomparison of MODIS, MISR, OMI, and CALIPSO Aerosol Optical Depth Retrievals for Four Locations on the Indo-Gangetic Plains and Validation against AERONET Data." *Atmospheric Environment* 111:113–26.

Eck, ET et al. 1999. “Wavelength Dependence of the Optical Depth of Biomass Burning, Urban, and Desert Dust Aerosols.” *Journal of Geophysical Research* 104(1).

Hess, M., P. Koepke, and I. Schult. 1998. “Optical Properties of Aerosols and Clouds : The Software Package OPAC.” *Bulletin of the American Meteorological Society* 79(5):831–44.

Holben, B.N., D.Tanre, A.Smirnow, T.F.Eck, I.Slutsker, N.Abuhassan, W.W.Newcomb, J.S.Schafer, B. Chatenet, F.Lavenu, Y.J. Kaufman, J. Vande Castle, A.Setzer, B.Markham, D.Clark, R.Halthore, A. Karneli, N.T. O'Neili, C.Pietras, R.T.Pinker, K. Vos. and G. Zibord. 2001. “An Emerging Ground-Based Aerosol Climatology.” *Journal of Geophysical Reasearch* 106(D11)(Dll):12 067–12 097.

Kalapureddy, M. C. R. et al. 2009. “Identification of Aerosol Type over the Arabian Sea in the Premonsoon Season during the Integrated Campaign for Aerosols, Gases and Radiation Budget (ICARB).” *Journal of Geophysical Research Atmospheres* 114(17):1–12.

Kant, Yogesh, Piyush Patel, A. K. Mishra, U. C. Dumka, and V. K. Dadhwal. 2012. “Diurnal and Seasonal Aerosol Optical Depth and Black Carbon in the Shiwalik Hills of the Himalayas: A Case Study of the Doon Vally, India.” *International Journal of Geology, Earth and Environmental Sciences* 2(2):173–92.

Kaskaoutis, D. G., K. V. S. Badarinath, Shailesh Kumar Kharol, Anu Rani Sharma, and H. D. Kambezidis. 2009. “Variations in the Aerosol Optical Properties and Types over the Tropical Urban Site of Hyderabad , India.” *Journal of Geophysical Reasearch* 114:1–20.

Kumar, Rajesh et al. 2011. “Influences of the Springtime Northern Indian Biomass Burning over the Central Himalayas.” *Journal of Geophysical Research Atmospheres* 116(19):1–14.

Levy, R. C. et al. 2010. “Global Evaluation of the Collection 5 MODIS Dark-Target Aerosol Products over Land.” *Atmospheric Chemistry and Physics* 10(21):10399–420.

Moorthy, K. Krishna. 1989. “Multiwavelength Solar Radiometer Network and Features of Aerosol Spectral Optical Depth at Trivandrum.” *Indian Jwmal of Radio& Space Physics* 18 :194–201.

More, Sanjay, P. Pradeep Kumar, Pawan Gupta, P. C. S. Devara, and G. R. Aher. 2013. “Comparison of Aerosol Products Retrieved from AERONET , MICROTOPS and MODIS over a Tropical Urban City , Pune , India.” *Aerosol and Air Quality Research* 13(1):107–21.

Patel, Piyushkumar N. and Raj Kumar. 2015. “Estimation of Aerosol Characteristics and Radiative Forcing during Dust Events over Dehradun.” *Aerosol and Air Quality Research* 15(5):2082–93.

Pawar, G. V., P. C. S. Devara, and G. R. Aher. 2015. “Identification of Aerosol Types over an Urban Site Based on Air-Mass Trajectory Classification.” *Atmospheric Research* 164-165:142–55.

Remer, Lorraine A. et al. 2008. “Global Aerosol Climatology from the MODIS Satellite Sensors.” *Journal of Geophysical Research Atmospheres* 113(14):1–18.

Ricchiazzi, Paul, Shiren Yang, Catherine Gautier, and David Sowle. 1998. “SBDART : A Research and Teaching Software Tool for Plane-Parallel Radiative Transfer in the Earth'S Atmosphere.” *Bulletin of the American Meteorological Society* 79:2101–14.

Satheesh, S. K. and K. Krishna Moorthy. 2005. “Radiative Effects of Natural Aerosols: A Review.” *Atmospheric Environment* 39(11):2089–2110.

Singh, S. et al. 2010. “Clear-Sky Direct Aerosol Radiative Forcing Variations over Mega-City Delhi.” *Annales Geophysicae* 28(5):1157–66.

Sinha, P. R. et al. 2013. “Contrasting Aerosol Characteristics and Radiative Forcing over Hyderabad, India due to Seasonal Mesoscale and Synoptic-Scale Processes.” *Quarterly Journal of the Royal Meteorological Society* 139(671):434–50.

Zheng, Youfei et al. 2008. “Seasonal Statistical Characteristics of Aerosol Optical Properties at a Site near a Dust Region in China.” *Journal of Geophysical Research Atmospheres* 113(16):1–11.