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Variability in aerosols properties and sources over Rohtak, India

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सार – वायुविलय की विकिरण संबंधी क्रियाओं में उनके महत्वपूर्ण प्रभावों के कारण जलवायु संबंधी अध्ययनों में महत्वपूर्ण भूमिका रहती है। इस अध्ययन में, स्काई-रेडियोमीटर POM-2 डेटा का उपयोग जून 2012- मई 2014 की अवधि के लिए रोहतक शहर में वायुविलय गुणों में दैनिक और मासिक परिवर्तनशीलता के स्रोत की जांच करने के लिए किया गया। पूरी अध्ययन अवधि के लिए AOD, Alpha, SSA और ASY के वार्षिक माध्य मान क्रमशः 0.71 ± 0.36, 0.74 ± 0.35, 0.93 ± 0.05 और 0.71 ± 0.02 थे। मॉनसून पूर्व महीनों के दौरान एओडी के उच्च मान और अल्फा के कम मान ने खुरदरे धूल कणों की अधिकता का संकेत दिया। नवंबर के महीने में, एसएसए (0.84 ± 0.01) के निम्न मान से उत्तर-पश्चिमी भारत में दिवाली के त्यौहार में धान की फसल के अवशेषों और पटाखों को जलाने से जुड़े अवशोषित वायुविलय की अधिकता का पता चला। वायुविलय अध्ययन का एक और महत्वपूर्ण प्राचल है जो बाइमोडल वितरण के साथ फाइन मोड कणों के लिए ~0.20 माइक्रोन पर पहली पीक और खुरदरे मोड कणों के लिए ~5 माइक्रोन पर एक दूसरी पीक प्रदर्शित करता है। एओडी और अल्फा के अनुपात का उपयोग करके वायुविलय को चार श्रेणियों में वर्गीकृत किया जाता है: डस्ट डोमिनेटेड (DD), बायोमास बर्निंग (BB), एंथ्रोपोजेनिक वायुविलय (AA), और मिश्रित प्रकार (MT)। मॉनसून पूर्व और मॉनसून ऋतु के दौरान डस्ट डोमिनेटेड (DD) वायुविलय को 26.4% और 19.8% के अंश के साथ अधिकतम पाया जाता है। बायोमास बर्निंग (BB) प्रकार के वायुविलय क्रमशः मॉनसूनोत्तर और शीत ऋतु के दौरान 34% और 30% के अंश के साथ प्रमुख होते हैं।

ABSTRACT. Aerosols are crucial species in climate-related studies due to their significant impacts on radiative forcing. In the present study, Sky-radiometer POM-2 data was used to investigate the source of daily and monthly variability in aerosol properties over Rohtak city for the period from June, 2012-May, 2014. The annual mean values of AOD, Alpha, SSA and ASY were 0.71 ± 0.36, 0.74 ± 0.35, 0.93 ± 0.05 and 0.71 ± 0.02, respectively for the entire study period. The higher value of AOD and the lower value of Alpha during pre-monsoon months indicated the dominance of coarse mode dust particles. During November month, the lower value of SSA (0.84 ± 0.01) suggesting the dominance of absorbing type aerosol which may be associated with the burning of paddy crop residue and firecrackers on Diwali festival, in North-Western India. Another crucial parameter for the aerosol study in volume size distribution which exhibits a bimodal distribution with the first peak at ~0.20 µm for fine mode particles and a second peak at ~ 5 µm for coarse mode particles. Aerosols are classified into four categories by using the ratio of AOD and Alpha: Dust Dominated (DD), Biomass Burning (BB), Anthropogenic Aerosol (AA) and Mixed Type (MT). Dust dominated (DD) aerosols are found maximum during pre-monsoon and monsoon seasons with a fraction of about 26.4% and 19.8%, respectively. Biomass burning (BB) type aerosols are dominant during the post-monsoon and winter seasons with a fraction of 34% and 30%, respectively.

Key words – AOD, SSA, Angstrom exponent, Volume-size distribution, Aerosol classification.

1. Introduction

The atmosphere is critically affected by rapid industrialization, urbanization, growing population and other anthropogenic activities in recent times. At present air pollution due to the higher load of atmospheric aerosols is a major problem people facing in an urban environment. Atmospheric aerosol influences daily weather, radiation balance and climatic conditions by regulating the amount of solar energy that reaches the earth's surface. Various remote sensing and ground-based studies have been carried for measurements of the aerosol load over the Indian region from the mid-1980s and all these have shown an increasing trend in aerosol loading (Moorthy *et al*., 2013; Acharya and Sreekesh, 2013) but still, there is large uncertainty in the assessment of seasonal variability and distribution of aerosol.

Atmospheric aerosol exhibits significant seasonal variability in properties and distribution over Northern India due to associated changes in source type, changing air masses and rainfall pattern (Singh *et al*., 2004; Jethva *et al*., 2005; Gautam *et al*., 2007; Gogoi *et al*., 2009; Kaskaoutis *et al*., 2009; Henriksson *et al*., 2011). Atmospheric aerosol varies in shapes, sizes and chemical composition based on their emission sources which play a decisive role in various atmospheric processes. Aerosol plays a major role in fog, mist and clouds formation in the lower troposphere whereas they produce electrical effects in the upper troposphere. In India, several studies have shown that a huge amount of elemental and organic carbon was generated from crop residue burning (Gadde *et al*., 2009; Rehman *et al*., 2011; Sahai *et al*., 2011), fossil fuel combustion in different sectors such as residential, industrial, transportation, etc. (Kandpal *et al*., 1995; Ghose and Majee, 2003; Mishra, 2004; Nesamani, 2010; Apte *et al*., 2011) and forest fires (Badarinath *et al*., 2007; Vadrevu *et al*., 2011).

North-Western India is one of the most populated and highly polluted regions over the globe (Kaskaoutis *et al.*, 2013; Tiwari *et al*., 2014a, 2014b). Aerosol showed strong variability in composition during the different seasons due to the mixing of anthropogenic and natural aerosol (Ramanathan and Ramana, 2005; Dey and Di Girolamo, 2010; Srivastava and Ramachandran, 2013). During pre-monsoon and monsoon months, northern India experiences higher aerosol loading due to dominant westerly winds that carries dust over the site from deserts (Dey *et al*., 2004; Lawrence and Lelieveld, 2010; Srivastava *et al*., 2011; 2012; Kaskaoutis *et al*., 2013). The monsoonal rainfall from mid-June to September partly removes the aerosol load over northern India (Rajeevan *et al*., 2006). During post-monsoon season fine mode aerosols were dominant over northern India which are contributed by the paddy crop residue burning (Kharol *et al*., 2012).

Various recent studies have suggested that profound knowledge of variability in aerosols properties and their distribution is required to completely understand their regional and global climatic impacts (Tiwari *et al*., 2009; Tiwari *et al*., 2015a). Therefore to understand the uncertainty in the estimation of radiative forcing and the role of aerosols in climate change there is a need for continuous monitoring of aerosols distribution and their seasonal, annual and long-term variability. It is also crucial to see how their changing pattern affects global and regional climate.

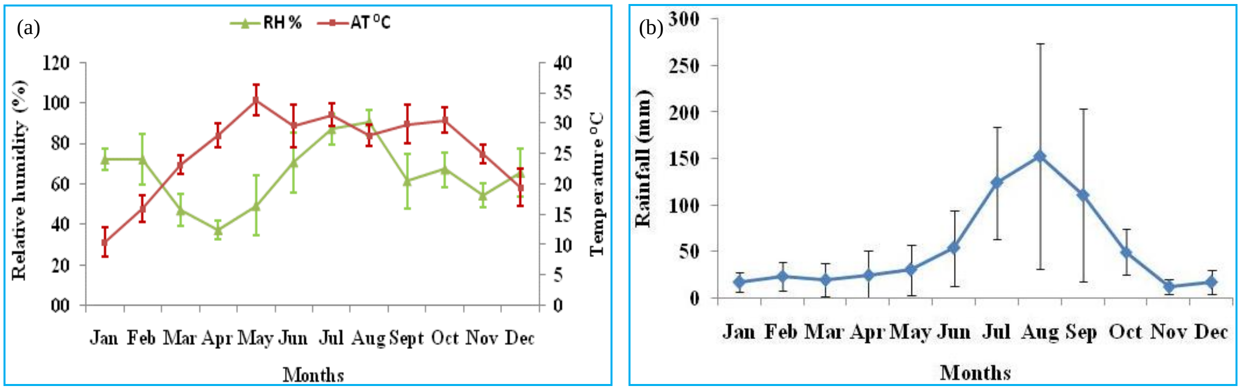
In the present study, we have analyzed monthly and seasonal variability in aerosol optical, physical properties and their size distribution over the Rohtak City, Haryana during the period from June-2012 to May-2014 to identify the source of variations. Rohtak is situated in the western part of the heavily populated and polluted Indo-Gangetic plains, which suffers from severe fog, dense haze and smog problems (Prasad *et al*., 2004; Gautam *et al*., 2007). In recent years, the rapid increase in energy consumption and vehicular pollution has caused serious aerosol pollution in Rohtak. Therefore, the assessment of aerosol properties is very useful to understand the regional effects of aerosol. We have analyzed the spectral variation in AOD, Ångström exponent (alpha), volume size distribution, single scattering albedo (SSA) and asymmetry parameters (ASY). Classification of aerosols is also done by using the AOD to Alpha ratio.

2. Sampling site and meteorological conditions

The present study pertains to Rohtak, an urban area in the northwest part of the Indo-Gangetic Basin. It lies between latitude 28.89° N and longitude 76.58° E, at 214 m above mean sea level. Like most of the Indian cities, it also has a mixed pattern of land use with ahuman population of 0.37 million as per the Census of India, 2011. Rohtak is surrounded by agricultural land, therefore, agricultural activities like the burning of crop residue also play a crucial role in the seasonal changes of its air quality. Rohtak is surrounded by Shivalik range from the North-East and by Aravali range from South-West. The study site is also surrounded by the Rajasthan's deserts towards the south.

Meteorology plays an important role in the atmospheric chemical reaction, the formation of secondary particles, their transport and dispersion (Harrison, 2001b). Therefore, the study of changes in local meteorological conditions such as wind speed, wind direction, rainfall, relative humidity and temperature are necessary to estimate the composition and concentration of aerosols. For relative humidity and temperature, data was obtained from the Haryana State Pollution Control Board Panchkula. Rainfall data was taken from the Indian Meteorological Department, New Delhi for a period, from 2005 to 2014. Wind speed and wind direction data were obtained from Automated Weather Station, installed by Indian Meteorological Department, New Delhi, near Maharishi Dayanand University, Rohtak.

The variation in monthly average atmospheric temperature over the study area is shown in Fig. 1(a). The



Figs. 1(a&b). (a) Monthly mean variability in relative humidity, temperature and (b) rainfall pattern

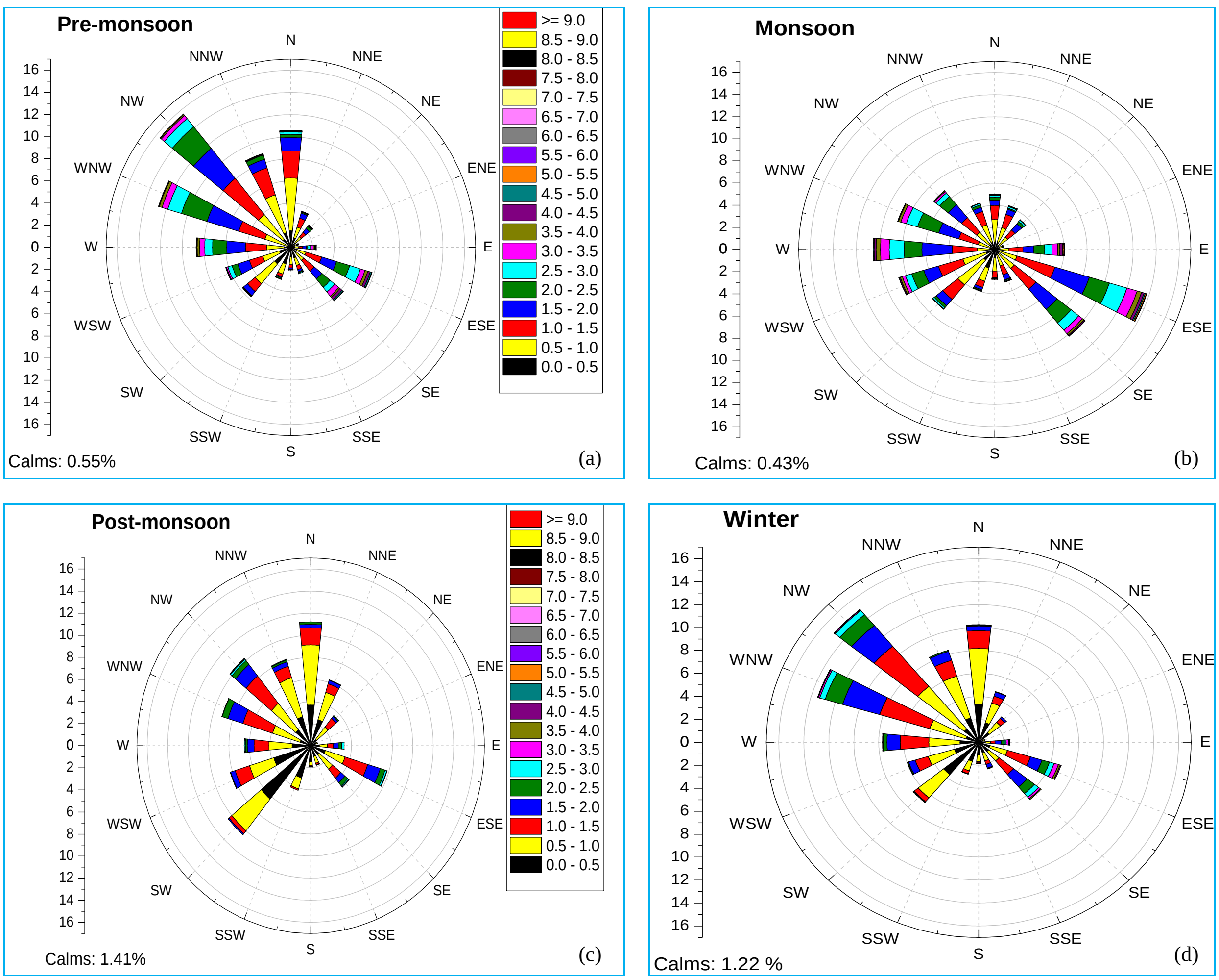
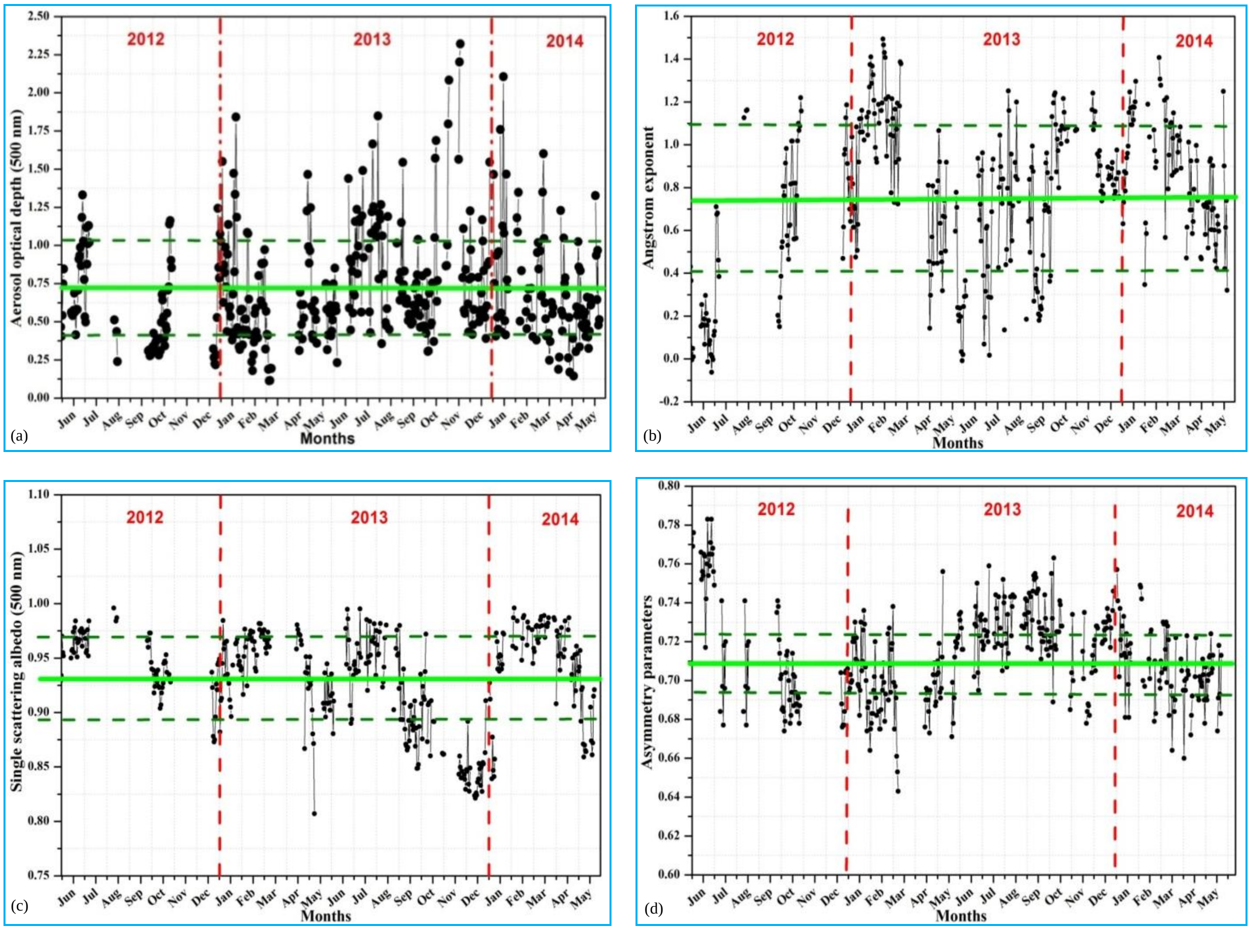


Fig. 2(a-d). Seasonal variation in wind speed (ms^{-1}) and direction during (a) pre-monsoon, (b) monsoon, (c) post-monsoon and (d) winter seasons for the period from June-2012 to May-2014

temperature ranged from 10.5 to 33.8 °C during the entire study period. The average minimum temperature was recorded during January whereas the maximum was observed during May. Over the study region, the monthly mean temperature showed an increasing trend from January and reach to the maximum during May. Afterward, it showed a relatively flat pattern from May to August with a slight decrease.



Figs. 3(a-d). Variations in daily average (a) AOD (b) Alpha (c) SSA and (d) asymmetry parameters

The average monthly variations of relative humidity are depicted in Fig. 1(a). It showed strong monthly variability with the values ranged from ~37% during April to ~90% during August. Relative humidity showed a steep decrease from February (~72%) and reached a minimum value during April (~37%). Afterward, it started rising again and reached to the maximum during August. Relative humidity remains consistently higher throughout the monsoon season and it again showed a decreasing trend after August up to November (~55%).

The rainfall acts as a natural scrubber and leads to lower particulate matter concentration during monsoon season. The highest rainfall was observed during August with a value of 152 mm while the lowest rainfall was observed during November with a value of 11 mm. The mean seasonal rainfall was highest during monsoon (July, August and September), which constitutes more than 60% of the average annual rainfall [Fig. 1(b)]. There was quite less rainfall during the winter and post-monsoon months of the study period.

Aerosols load in the atmosphere greatly depends on wind speed and wind direction, as these are the fundamental parameter, which affects the turbulence and long-range transport of dust aerosols. Seasonal variations in wind speed (ms^{-1}) and direction from June-2012 to May-2014 are shown in the form of a wind rose in Figs. 2(a-d). Over the study site, the higher wind speed was observed during the pre-monsoon and monsoon months while lower during the post-monsoon and winter seasons. The highest wind speed of about 8 ms^{-1} was reported during the monsoon season. Generally, the direction of prevailing winds is from northwest during the winter and pre-monsoon seasons and northwest to southwest during monsoon season. During the pre-monsoon season, predominant winds were from northwest and west-north-west and these are generally dry and rich in continental dust aerosol. During monsoon season, predominant winds were from west-north-west to southwest except for few times when there was east-south-east winds are predominant. During the post-monsoon season, wind rose showed wide distribution with predominant winds from North to southwest direction. During winter and post-monsoon seasons, the wind speed was very low and about 1.3% calm conditions were present.

3. Instrumentation

Sun/sky radiometer (Model POM-02; Prede Co. Ltd, Japan) located in the premises of Maharshi Dayanand University, Rohtak has been used to analyze aerosol properties. This instrument can make measurements of both direct and diffuse sky radiances at predefined scattering angles at regular intervals within the spectral range of 340-2200 nm. The wavelengths 340, 380, 400, 500, 675, 870 and 1020 nm are used to retrieve aerosol optical properties. SKYRAD.pack version 4.2 developed by the Nakajima *et al*. (1996) was used to retrieve aerosol properties from measured sky-radiometer data. *In situ* calibration constant was done by using the improved Langley plot technique (Campanelli *et al*., 2004). Structure and inversion accuracy of SKYRAD.pack are discussed in detail elsewhere (Nakajima *et al*., 1996; Tonna *et al*., 1995).

4. Results and discussion

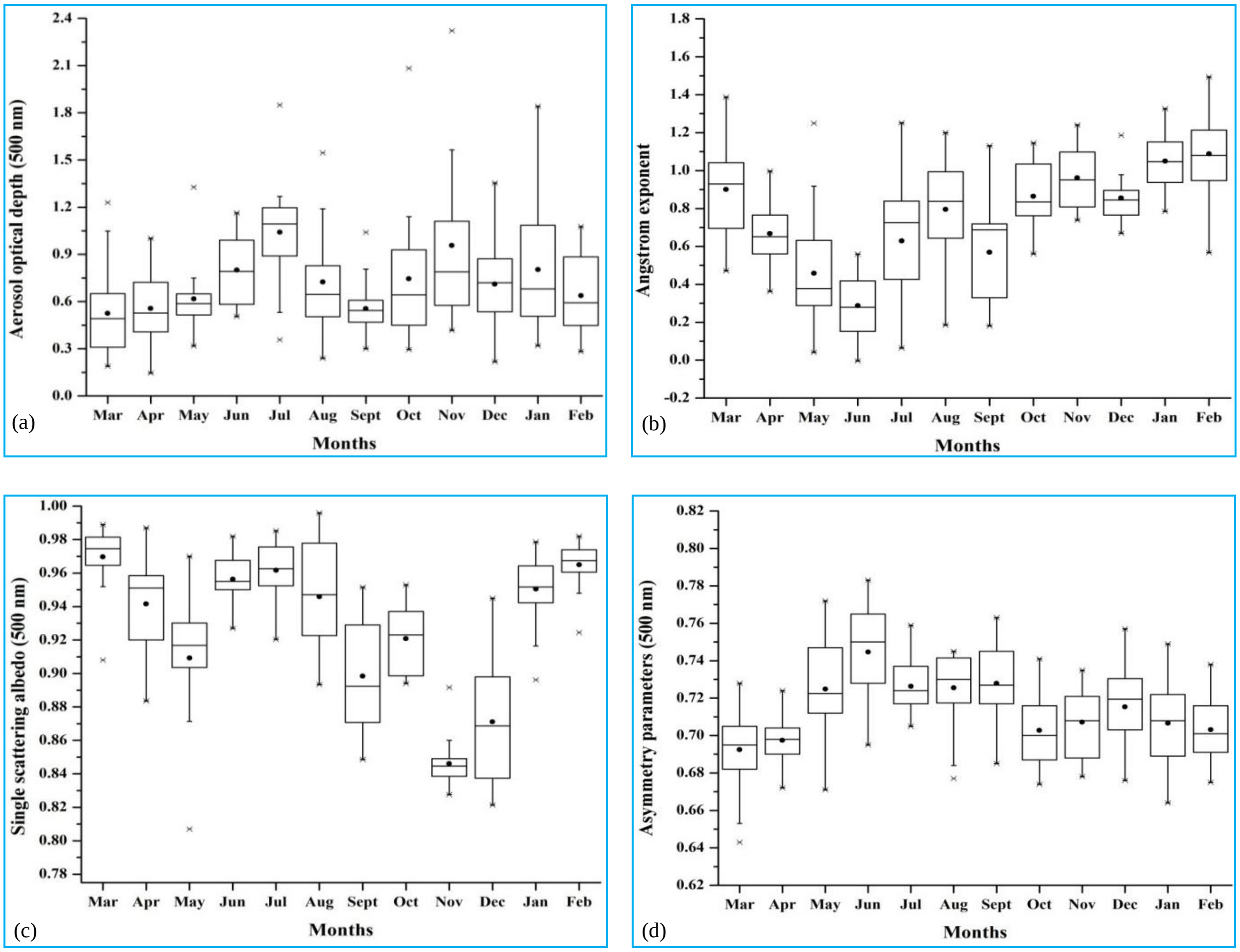
4.1. *Daily variations of aerosol optical properties*

During the study period, sometimes data was not available due to cloudy conditions, technical problems and power failure. In graphs, the mean value is shown with a bold line, whereas the standard deviation is shown with a dotted line. Variability in daily average AOD at 500 nm is shown in Fig. 3(a). The large scatter of AOD indicated the significant variability in the source of emission, boundary layer dynamics, atmospheric conditions and long-range transport of aerosol. The range of variability over Rohtak (0.11 to 2.32) was comparatively lesser than that found over Delhi (0.18 to 3.0) (Lodhi *et al*., 2013). The mean value of 0.71 ± 0.36 indicates the prevalence of severe aerosol loading over Rohtak, throughout the year. The mean AOD at 500 nm over Rohtak was relatively less as compared to the mean value (0.82) reported over Greater Noida (Sharma *et al*., 2014) and (0.78) over Delhi (Lodhi *et al*., 2013). Rohtak is less populated and industrialized as compared to the Delhi and Greater Noida; therefore, the mean AOD over Rohtak is comparatively less. But the observations of the present study were comparable with other sites of Indo Gangetic Plain (Giles *et al*., 2011; Tiwari *et al*., 2015a; Alam *et al*., 2012). In the present study, during November-2014 few very high peaks have been observed which were indicated the higher load of aerosols due to the burning of firecrackers on the Diwali festival and the burning of agriculture residue nearby areas. For a few days, very low values were observed, whereas more than 50% (207 out of 410 data points) were above 0.6 indicating higher aerosol loading over the study area.

From Fig. 3(b) it is evident that the Angstrom exponent showed strong variability in scatter plot with the lowest value of -0.06 and the highest value of 1.49, this indicated the presence of aerosols of different sizes with significant variability in daily and seasonal atmospheric conditions. The mean value of 0.74 ± 0.35 was observed for the whole study period suggesting the dominance of fine mode aerosols over the study region. The mean value observed over Rohtak was relatively less than the mean values of 0.82 over Delhi (Tiwari *et al*., 2016) and 0.95 over Greater Noida (Sharma *et al*., 2014). The smaller value of Angstrom exponent over Rohtak suggested the less concentration of anthropogenic fine mode aerosols as compared to the densely populated urban areas like Delhi and Greater Noida. The observations of the present study were comparatively higher than the Angstrom exponent values reported over Ahmedabad (0.67) by Ganguly *et al*. (2006). The lower values of Angstrom exponent over Ahmedabad indicated the dominance of coarse mode aerosol due to the proximity of the desert. About 50% of Angstrom exponent values (196 out of 410 data points) were greater than 0.8, which indicates the presence of mixed type aerosol from both anthropogenic and natural sources.

From Fig. 3(c) it was evident that the SSA showed a significant variability over the study region with the values ranging from 0.80 on 19th April, 2013 to as high as 0.99 on 8th July, 2012. The range of variation (0.80 to 0.99) was relatively lesser than as reported by Ram *et al*. (2016) over Kanpur (0.67 to 0.92). The mean value of SSA at 500 nm (0.93) was greater than the values observed by Singh *et al*. (2010) over a nearby station Delhi (~0.80). Higher SSA over Rohtak as compared to Delhi represents the dominance of scattering-type aerosol. Delhi is much densely populated and urbanized due to which there is a higher emission of carbonaceous aerosol from bio-fuel burning and vehicular emission; which leads to lower SSA value. The observation over the present site was also lowered than that observed over Kanpur (0.78) (Ram *et al*., 2016). The daily mean value of SSA at 500 nmwas 0.93 ± 0.04, indicated the dominance of scattering-type aerosols over the study region. About 77% of SSA values were larger than 0.9 (313 out of 410 data points) suggesting the dominance of scattering-type aerosol.

The large scatter plot of the Asymmetry parameter as shown in Fig. 3(d) suggested a stronger variability in asymmetry parameter values with a minimum value of 0.64 and a maximum value of 0.78. The lowest value was observed on 4th March, 2013 whereas the highest was observed on 21st June, 2012. Adesina *et al*. (2014)



Figs. 4(a-d). Monthly variations in (a) AOD, (b) Alpha, (c) SSA and (d) ASY at 500 nm

reported a decrease in asymmetry parameters due to the dominance of fine mode anthropogenic aerosol. The higher value during June suggested the abundance of coarse mode aerosol. Alam *et al*. (2011) reported asymmetry parameter value ranged from 0.61 to 0.71 over Karachi for the period from August-2006 to July-2007, which is comparable with the results of the present study. The mean value of the daily asymmetry parameter was 0.71 ± 0.02 for the whole study period suggesting the presence of mixed-type aerosol of fine mode urban origin and coarse mode dust aerosol. About 51% of values were found less than the mean value (215 out of 410) indicating the mixed type aerosol over the station.

4.2. *Monthly variation in aerosol properties*

Monthly variability in aerosol properties was plotted in Box plots. In the chart, solid dots represent the mean and the median is represented by divisory lines in the box. The upper and lower limits of the box represent the standard deviation. The box bars correspond to 5% and 95% percentiles whereas 1% and 99% percentiles are represented by crosses.

4.3. *Aerosol Optical Depth (AOD)*

The monthly variability in AOD at 500 nm is shown in Fig. 4(a). The highest monthly mean (median) value of AOD at 500 nm during July [1.04 ± 0.34 (~1.09)] may be associated with higher loading of coarse mode dust aerosols due to long-range transport of dust particles as dust storm activities are at their peak during pre-monsoon period. The results are quite comparable to those reported by Sharma *et al*. (2014) over Greater Noida and Singh *et al*. (2004) over Kanpur. A similar result was reported by Tiwari *et al*. (2016) over New Delhi. Tiwari and Singh *et al*. (2013) also reported higher AOD due to enhancement in coarse mode particles over Varanasi.

Higher values of AOD during November may be associated with the dominance of fine mode aerosol due to paddy crop residue burning (Tiwari *et al*., 2016).

Sharma *et al.* (2010) and Kharol *et al*. (2012) also reported higher AOD due to agriculture crop residue burning over Punjab. The lowest monthly mean (median) AOD for March [0.52 ± 0.27 (~0.49)] shows transparent conditions before the start of dust storm activities from April. Lodhi *et al*. (2013) and Tiwari *et al*. (2016) also reported the lowest AOD during March over Delhi. Asnani *et al*. (1993) also reported lower AOD during the transition months of March and September over Pune. AOD exhibits a tri-modal annual pattern with the higher values during (1.04) July, (0.96) November and (0.80) January. The lowest values were observed in transition months, March (0.52) and September (0.55), during the study period. The annual tri-modal pattern observed over Rohtak is quite comparable to that which was observed over Indo-Gangetic Plain in various studies (Tiwari *et al*., 2016; Sharma *et al*., 2014; Lodhi *et al*., 2013; Wang *et al*., 2011; Giles *et al*., 2011).

4.4. *Angstrom exponent*

Monthly variability in the Angstrom exponent was shown in Fig. 4(b). The monthly mean Angstrom exponent ranged ~0.29 ± 0.17 in June to ~1.08 ± 0.19 in February. Larger variation in the range of Angstrom exponent was observed during pre-monsoon and monsoon months as compared to the post-monsoon and winter months. This indicates the variability in aerosol types and the source region. Significant variability in monthly mean Angstrom exponent suggested the multiple emission sources and particle size (Tiwari *et al*., 2016; 2015a). Nearly similar monthly variation for angstrom exponent has been reported in earlier studies over other sites of Indo-Gangetic plain (Gautam *et al*., 2011; Srivastava *et al*. (2012). The higher value of Angstrom exponent during winter and post-monsoon seasons suggested the enhancement in fine mode aerosol, which can be attributed to the emissions from biomass burning and crackers burning during the Diwali festival. Lodhi *et al*. (2013) and Srivastava *et al*. (2012) also reported the dominance of fine mode aerosols during winter and post-monsoon months.

The value of Angstrom exponent (~0.29) during June was slightly higher than that was reported by Alam *et al*. (2011) over Karachi (0.19). Soni *et al*. (2011) and Kaskaoustis *et al*. (2013) also reported the abundance of large size particles over Delhi due to the long-range transport of dust aerosol from Thar and Middle East deserts. More homogeneity in the range of Angstrom exponent was observed during winter and post-monsoon months suggested the more sources of aerosol's emission. Asimilar kind of homogenous source of emission and atmosphere was observed over Dibrugarh (Pathak *et al.*, 2013), Kanpur (Kaskaoutis *et al*., 2012) and Hyderabad (Sinha *et al*., 2012) during winter and post-monsoon months.

4.5. *Single Scattering Albedo (SSA)*

Variation in monthly mean SSA at 500 nm is depicted in Fig. 4(c). SSA showed strong monthly variability with the mean (median) values ranged from 0.84 (0.85) to 0.97 (0.98) during November and March months, respectively. SSA greatly depends on the chemical composition of aerosols, which vary significantly every month due to variations in the source of aerosol emission (Ram *et al*., 2016; More *et al*., 2013). The highest value of monthly mean SSA (0.97) was observed during March suggested the relative dominance of scattering-type aerosol than absorbing type aerosols. The SSA during March was comparable with that reported by Liu *et al*. (2008) over Northwest China (0.95). This was comparatively much higher than those observed over other sites of Indo-Gangetic Basin, such as 0.85 over Hyderabad (Sinha *et al*., 2013), 0.89 over Delhi (Tiwari e*t al*., 2015); 0.74 over Delhi (Ram *et al*., 2016).

The lower value of SSA was observed during November, which may be attributed to the enhancement of absorbing aerosols due to crop residue burning. Sinha *et al*. (2013) and Kumar *et al*. (2011) also showed lower values of SSA during post-monsoon months due to more contribution from biomass burning. Burning of crackers on Diwali and Dusshera during October and November also contributes to the enhancement of absorbing type aerosol and leads to a decrease in SSA value (Singh *et al*., 2014). SSA showed an increasing trend from May to August due to the dominance of water-soluble aerosol. Singh *et al*. (2004) and Alam *et al*. (2011) also reported higher SSA values during June-July due to the enhancement in water-soluble dust aerosol which grows hygroscopically in the presence of higher relative humidity.

4.6. *Asymmetry parameter (ASY)*

The monthly variability in the asymmetry parameter is depicted in Fig. 4(d). The asymmetry parameter depends on both the composition and distribution of aerosol (Ramachandran and Rajesh, 2008). The monthly mean value of symmetry parameter ranged from 0.69-0.75 over Rohtak was comparable with that reported by Adesina *et al*. (2015) over Gorongosa in Mozambique. The range of 0.64-0.83 has been observed by d'Almeida *et al*. (1991) for dry aerosol at 500 nm. Higher values of asymmetry parameter during June (0.75) is in close agreement with that reported by Alam *et al*. (2011) over Karachi (0.74). Alam *et al*. (2014) also reported the higher value of the asymmetry parameter for the dust-

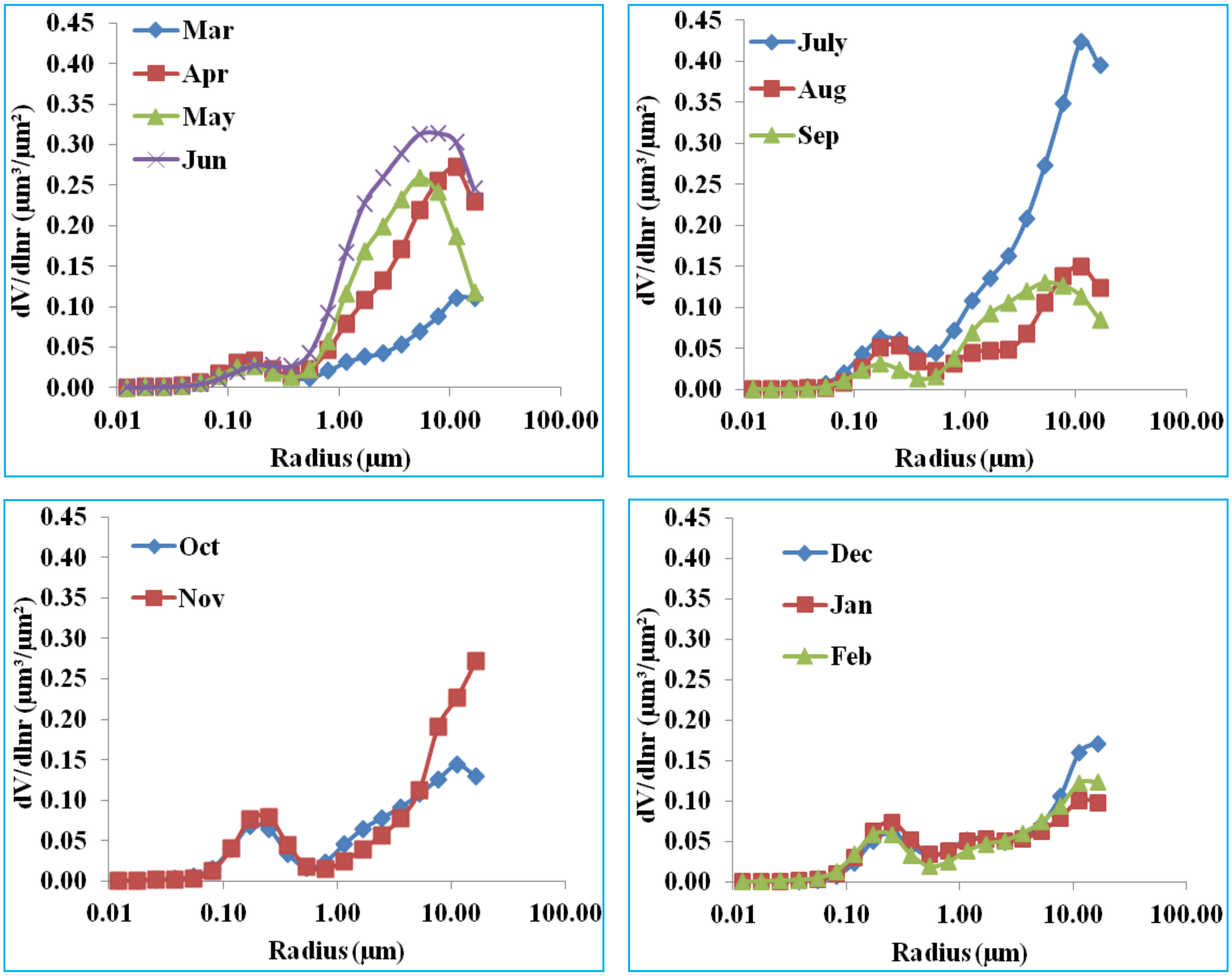


Fig. 5. Monthly variations in volume size distribution from June-2012 to May-2014

dominated period over the Middle-East and South-West Asia. The lowest values during March-April (~0.69) are comparable to the results observed over (~0.69) Gandhi College and Kanpur by Srivastava *et al*. (2011). The negative gradient of the asymmetry parameter during post-monsoon and winter months suggests the dominance of fine mode aerosols.

4.7. *Volume-Size distribution*

The radiative and climatic effect of aerosol depends not only on the aerosol loading in the atmosphere but also on their size. Volume size distribution is an important physical parameter for clearly differentiating the fine and coarse mode particle fractions in the atmosphere and to understand their effect on climate. Fig. 5 illustrates the monthly variation in aerosols size distribution retrieved from sun-sky radiometer measurements. The volume/size distribution exhibits a bimodal structure with the fine mode ~0.20 µm and the coarse mode ~ 5 µm. The highest volume of fine mode was observed during November while the lowest volume was observed during May. Coarse mode aerosol volume is highest during June-July whereas the lowest during January. The result showed the bimodal structure of volume/size distribution. The similar results of bimodal distribution have been reported by various researchers over the Indo-Gangetic Plain (Giles *et al*., 2011; Pandithurai *et al*., 2008; Patel and Kumar, 2015).

The high volume of fine mode aerosol during November may be associated with the agriculture residue burning and fireworks on the occasion of the Diwali festival. During June and July, the highest volume of coarse mode particles was observed, which may be attributed to the dominance of dust particles from dust raising activities. During pre-monsoon months, dust storms were very frequent over North-Western India

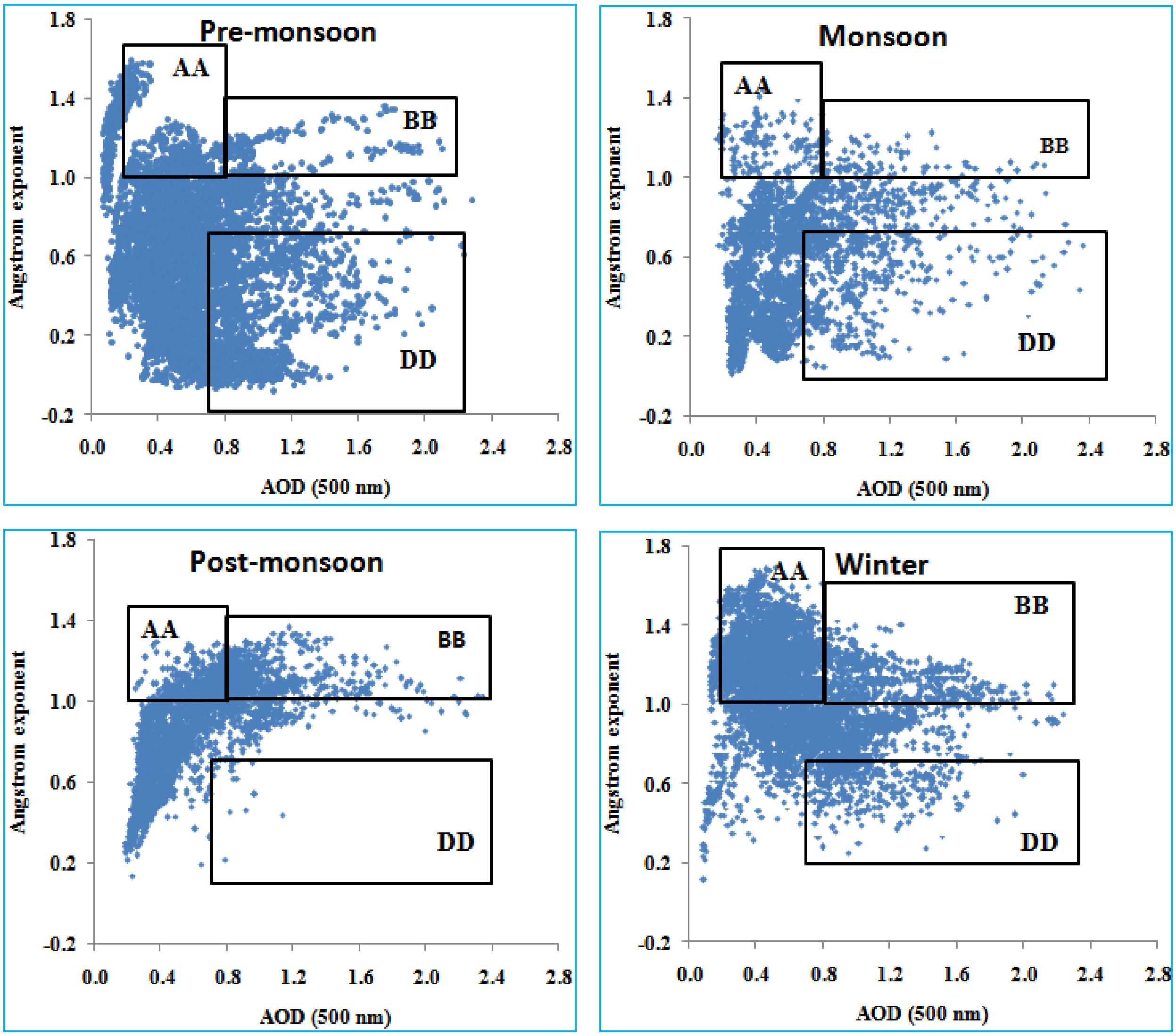


Fig. 6. Scatter plot between AOD and Angstrom exponent with the data points identifying dominant aerosols from June-2012 to May-2014

which leads to long-range transport of dust aerosols from desert areas over the study region. Therefore, a higher volume of coarse mode aerosol was found during the pre-monsoon months. Patel and Kumar (2015) have reported a higher volume of coarse mode aerosol over Dehradun during June which was comparable to the present study.

The monthly distribution of fine mode showed steady variation in fine mode aerosol volume as compared to the coarse mode volume. The fine mode aerosols were mainly related to the anthropogenic activities, therefore, they showed fewer variations. While the coarse mode aerosols were related to the dust storm activities which showed larger variability from month to month due to variability in atmospheric conditions. Liu *et al.* (2008) also observed similar results over Northwest China.

4.8. *Aerosol classification*

Aerosol's optical and physico-chemical properties vary significantly with the change in emission sources. From the above results, it was clear that mixed-type aerosols were present over Rohtak therefore; a detailed classification of aerosols was required to understand different types of aerosols. The relation between intensive and extensive properties of aerosols helps in determining the different types of aerosols (Holben *et al.*, 2001). Aerosol classification can be achieved with the help of different methods like the spectral dependence of SSA (Eck *et al.*, 1999), the correlation between Fine-mode fraction and SSA (Lee *et al.*, 2010) and the correlation between absorption and extinction Angstrom exponent (Giles *et al.*, 2011). Several researchers have used a scatter plot between AOD and Angstrom exponent as the most common and valid method for the classification of aerosols (Xia *et al*., 2016; Sharma *et al*., 2014; Tiwari *et al*., 2016; Yu *et al*., 2016b; Patel and Kumar, 2015).

In the present study, we have used a scatter plot between AOD (500) and Angstrom exponent to classify the aerosol. The threshold values used for scatter plot between AOD and Angstrom exponent were different for different locations based on variation in meteorology, aerosols characteristics and range of AOD (Kaskaoutis *et al*., 2009). Threshold values for AOD and Angstrom exponent for dust dominated (DD), biomass burning (BB), anthropogenic aerosol (AA) were taken as 0.7 and <0.7, >0.8 and >1.0, 0.2-0.8 and >1.0 for the present study. The threshold values used in the present study were slightly different from those reported by Tiwari *et al*. (2016) over Delhi and Sharma *et al.* (2014) over Greater Noida, because over these sites AOD was higher as compared to Rohtak. The cases which were not belonging to any group were considered as mixed type (MT) aerosols.

A scatter plot between AOD and Angstrom exponent for the classification of aerosol type is shown in Fig. 6. From the figure, it was observed that during all season dominant aerosol type was a mixed type (MT) with a contribution of 61.5%, 65.2%, 54.7% and 62.6% during pre-monsoon, monsoon, post-monsoon and winter seasons, respectively. Sharma *et al*. (2014) have identified dominant aerosol type over Greater Noida during the period 2010-2012 and found that (48 to 51%) fraction of mixed type during pre-monsoon and monsoon seasons. But very less fraction about 25% was observed during winter and post-monsoon seasons. In the present study, mixed type (MT) aerosol showed more contribution as compared to other sites of Indo-Gangetic Plain. Tiwari *et al*. (2016) found a very less amount of mixed type aerosol over Delhi fromApril-2011 to March-2013. For the mixed type aerosol, results observed over Rohtak were comparable with the observation of Kumar and Patel (2015) over Hyderabad. Kang *et al*. (2016) reported the 46.33% fraction of mixed type (MT) aerosol over Ninjing China.

Dust dominated (DD) aerosols were dominated during pre-monsoon and monsoon seasons with a fraction of about 26.4% and 19.8%, respectively. On the other hand, DD type rarely found during post-monsoon and only a small fraction of about 5% was observed during winter. These results suggested the dominance of coarse mode type DD aerosol due to higher dust storm activities. HYSPLIT back trajectories also suggesting the long-range transport of dust aerosols and sea salts from the Thar Desert and the Arabian Sea during pre-monsoon and monsoon seasons. Biomass burning (BB) type aerosols were dominated during post-monsoon and winter seasons with afraction of 34% and 30%, respectively; while during pre-monsoon and monsoon, this fraction was less than 5%.

From the results, it is evident that dominant aerosol during winter and post-monsoon were BB type, due to the higher rate of biomass burning for heating purposes and crop residue burning during November were the major sources of fine mode biomass burning aerosols. Results of the present study were comparable with (Tiwari *et al*., 2016) over Delhi. Ramachandran *et al*. (2012) have reported the higher contribution of Black carbon and anthropogenic aerosol during post-monsoon and winter seasons. Similar observations of abundance biomass burning (BB) aerosol have been reported Zhu *et al*. (2016) over Kunming and Yu *et al*. (2016b) over Beijing.

5. Conclusions

The present study was conducted over Rohtak city (Haryana) from June-2012 to May-2014 for analyzing daily and monthly variability in aerosol properties by using the sky-radiometer data. The daily mean values of AOD, Alpha, SSA and Asymmetry Parameter ranged from 0.11 to 2.32, -0.06 to 1.49, 0.84-0.97 and 0.69-0.75 for the entire study period. The highest value of monthly mean (AOD) was observed (1.04 ± 0.34) during July and the lowest (0.52 ± 0.27) during March. Higher AOD values during July may be associated with the long-range transport of dust aerosol and sea salt particles. The monthly mean Angstrom exponent ranged between ~0.29 ± 0.17 during June to ~1.08 ± 0.19 during February. This indicated the dominance of coarse mode aerosol due to dust storm activities during June and the dominance of fine mode aerosol from anthropogenic activities during February. SSA showed strong monthly variations with the mean (median) values ranged between 0.84 ± 0.01 (0.85) and 0.97 ± 0.02 (0.98) during November and March, respectively. The lowest value of SSA during November indicated the dominance of absorbing type Black carbon aerosol due to paddy crop residue burning. The highest mean (median) value of the asymmetry parameter was observed during June 0.75 ± 0.02 (~0.75) while the lowest value was observed during March-April 0.69 ± 0.2 (~0.72). The higher value of the asymmetry parameter during June suggested the more scattering in the forward direction due to the dominance of coarse mode dust aerosol. Volume size distribution is an important physical parameter for clearly differentiating the fine and coarse mode particle fractions in the atmosphere. It exhibits a bimodal structure with the fine mode ~0.20 µm and the coarse mode ~ 5 µm. The highest volume of fine mode was observed during November while the lowest volume was observed during

May. The scatter plot between AOD at 500 nm and the Angstrom exponent was used to classifying the dominant aerosol type. During all seasons, mixed type (MT) aerosols were dominated with the contribution of 61.5%, 65.2%, 54.7% and 62.6% during pre-monsoon, monsoon, post-monsoon and winter seasons, respectively. Dust dominated (DD) aerosols were dominated during pre-monsoon and monsoon seasons with a fraction of about 26.4% and 19.8%, respectively. Biomass burning (BB) type aerosols were dominated during post-monsoon and winter seasons with a fraction of 34% and 30%, respectively.

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