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Seasonal variation and classification of aerosols over an inland station in India

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ABSTRACT: Aerosols are capable of interfering with the radiation balance and cloud properties of the Earth-atmosphere system. The present study analyses and classifies the aerosol properties over a station, Kanpur, located in the Gangetic plain, which is the area with maximum aerosol loading in Indian subcontinent. Kanpur is one of the highly populated and industrialized cities in north India and is a good source of natural and anthropogenic aerosols. The analysis of aerosol characteristics reveals that aerosol loading is highest during the months of May to June and November to January. Accumulation mode aerosols (mainly of anthropogenic origin) dominate over coarse mode aerosols in the winter and post-monsoon seasons. During the summer, coarse mode aerosols dominate in the atmosphere. A comparison of sunphotometer data with satellite data shows lowest correlation during monsoon season. The satellite derived aerosol optical depth is overestimated during the monsoon season. Atmospheric aerosols are grouped and classified into different clusters according to their optical and microphysical properties. Three clusters were identified and defined according to features of the location and aerosol microphysical properties over the station. The classified clusters are defined as: (1) urban fine aerosols; (2) heavy pollution, and, (3) urban mixed aerosols. Of these heavy pollution episodes occur least and urban fine aerosols are observed at the highest number of occurrence. Wind has significant impact in the determination of local aerosol properties by advection of the particles from other locations and enhancing dust storm activities.

KEY WORDS aerosol optical depth; Angstrom exponent; AERONET; cluster analysis

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1. Introduction

Aerosols affect the climate of the Earth-atmosphere system by interaction with radiation of different wavelengths (Charlson *et al*., 1999). Absorption and reflection by aerosols have a significant effect in the determination of climate forcing (Chou *et al*., 2005). Global dimming, an observed decrease in the absorbed solar radiation, is an emerging issue related to aerosol pollution among the atmospheric science community (Pinker *et al*., 2005). Ramanathan *et al*. (2005) reported a reversal in dimming over several locations across India. Disparities in aerosol source, type and amount affect the surface fluxes and precipitation on a regional scale. For example, the monsoon system over India is altered by the large magnitude of aerosol loading over the Ganga Basin (Niogi *et al*., 2007). Also, air trajectories are capable of advecting aerosols from one region to another and make a substantial impact on the aerosol properties over the destination (Tyson *et al*., 1996). Thus, regional aerosol properties vary due to the local emission and advected particles from other locations.

In the present study, aerosol characteristics over Kanpur (26°28′N to 80°21′E), situated on the Indo-Gangetic plain, are analysed using AERONET (Aerosol Robotic Network) sunphotometer station data. The role of aerosol transport on regional particle properties was analysed and the aerosols are classified according to optical and microphysical properties. Kanpur is a highly populated and industrially developed city located within the Ganga Basin. It is the ninth most populated city within India with a population of 5 million. The station experiences a humid subtropical climate with a long hot summer, and mild and relatively short winters. The station is also characterized by the activity of the summer monsoon and dust storm events. It receives monsoon rainfall during July to September.

Dust storms refer to the strong dust-carrying windstorms that transport great quantities of dust and other fine grains into the atmosphere. Dust storms are caused by strong winds blowing over loose soil or sand, and often occur in arid and semi arid regions, especially in subtropical latitudes. They raise much material into the atmosphere and reduce the visibility greatly. The dust storms cause large amount of erosion, transport and deposition of mineral aerosols (Goudie, 1983) and thereby stand as significant sources of aerosol loading during dry summer seasons. The seasonality of the dust storms is controlled by different factors such as rainfall, soil moisture conditions, vegetation cover, temperature and surface winds. During rainy seasons the dust storms do not occur, due to the increase in soil moisture due to precipitation. According to the WMO (World Meteorological Organisation) protocol, dust events are classified according to visibility into the following categories.

1. Dust-in-suspension: widespread dust in suspension, not raised at or near the station at the time of observation; visibility is usually not greater than 10 km;
2. Blowing dust: raised dust or sand at the time of observation, reducing visibility to 1–10 km;
3. Dust storm: strong winds lift large quantities of dust particles, reducing visibility to between 200 and 1000 m, and,
4. Severe dust storm: very strong winds lift large quantities of dust particles, reducing visibility to less than 200 m.

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Ground-based instruments provide reliable information on aerosol properties. AERONET is a network of sunphotometers installed at different locations across the world. The Indo Gangetic Basin is highly polluted by aerosols during both summer and winter (Jethva *et al*., 2005). The studies of seasonal aspects of aerosol optical properties over Kanpur by Singh *et al*. (2004) infer the presence of dust and urban aerosols over the station. On the basis of their study, dusty conditions are mostly found during the summer, whilst urban aerosols dominate during the winter due to anthropogenic activities.

Aerosol Optical Depth (AOD) and inversion data obtained from Kanpur meteorological station are used to classify aerosols into different clusters, defined on the basis of their optical and microphysical properties and the geographical features of the location. Cluster analysis is an effective method for the purpose of classification of a collection of observations into different groups based on similarities in properties. A range of clustering algorithms is available in order to determine the pollutant types (Kaufman and Rousseeuw, 1990; Hwang and Hopke, 2007). Omar *et al*. (2005) made classification of aerosol types using cluster analysis based on the AOD and inversion data derived from 200 AERONET stations around world.

2. Data and methodology

AERONET station data at 1020, 500 and 380 nm wavelengths for Kanpur (2001–2008) are used in the present analysis. The data represent aerosol observations in the near-infrared, visible and ultra violet (UV) wavelengths. Level-2 quality-assured data are used for the present study. The sun/sky radiometer measures the direct Sun and diffuse sky radiances within the spectral range 340–1020 nm. Direct Sun observations are made at 340, 380, 440, 500, 670, 870, 940 and 1020 nm wavelengths. The 940 nm channel is used to measure water vapour content and the remaining channels are used to estimate AOD. A detailed description about the CIMEL sunphotometer installed at the AERONET stations is available in Holben *et al*. (1998). Spectral variation of AOD is used to identify the size distribution of aerosols within the total aerosol content. The Angstrom exponent derived from observations at 440 and 675 nm wavelengths is useful in the determination of the mean size of aerosol particles. High values of exponent indicate a majority of sub-micron accumulation mode aerosols. Terra MODIS monthly aerosol data with $1^\circ \times 1^\circ$ resolution for 2001–2008 is also used for comparison purposes. NCEP/NCAR monthly wind data with $2.5^\circ \times 2.5^\circ$ resolution (Kalnay *et al*., 1996) are used to determine the effect of the circulation pattern on aerosol properties over the station. Monthly air temperature data from NCEP/NCAR are also used in order to analyse the surface air temperature over the station. TRMM (Tropical Rainfall Measuring Mission) accumulated precipitation data with $0.25^\circ \times 0.25^\circ$ resolution are used to understand the temporal variation of the rainfall. A Hybrid Single Particle Langrangian Integrated Trajectory (HYSPLIT) model is used for trajectory analysis in order to understand the sources and transport of the aerosol particles (Draxler and Hess, 1997). The model uses three-dimensional wind data from NCEP/NCAR as input in order to find the trajectories of air parcels. Three-dimensional wind data converted into a model-compatible format are available from the NOAA Air Resourced Laboratory (ARL) website.

Aerosols are classified from the observed parameters using cluster analysis. The parameters used and cluster types are shown in Table 1. The optical and microphysical properties of aerosols are classified adopting K-means cluster analysis using selected parameters from aerosol inversion data obtained from the AERONET station. In K-means clustering (MacQueen, 1967), the data points are combined into a number of clusters and each point belongs to the cluster with its nearest centroid. Three numbers of clusters are identified using Ward's method (Ward, 1963) in an automated hierarchical clustering method.

3. Results and discussions

3.1. Monthly variation of AOD and Angstrom exponent over Kanpur

Using AERONET sunphotometer data (500 nm), monthly mean AOD and the Angstrom exponent (Figure 1) were analysed over Kanpur. AOD is found to be high, with values around 0.8, during the months of May and June and around 0.7 during the months of November to January. The other months show less aerosol loading, with optical depth value below 0.6. AOD values never fall below 0.4 on an annual basis. Variation of the Angstrom exponent, with minimum value during April to June, suggests that coarse mode aerosols dominate during the summer. The October to February period shows values of the Angstrom exponent above 1, indicating a good fraction of sub-micron particles in the total aerosol content during the winter. The Monsoon reaches north India only by the third week of June and covers the entire area of India by the second week of July, even though the date of onset in southern India is 1 June. Kanpur receives most of its rainfall between the last week of June and September. During the first half of June, dry conditions prevail over north India. A lack of soil moisture increases the production rate of natural aerosols such as soil dust and they are not removed from the atmosphere by rainfall. From July onwards, a decrease in AOD is detected, up to the month of September. However, the AOD is also high in July (around 0.6), which points to high aerosol loading.

During April to July, the 1020 nm AOD is observed to be high, with a maximum in May and June (0.6). It is obvious from these observations that the fine mode aerosol concentration

Table 1. Final cluster centres using 18 parameters.

	Cluster		
	1	2	3
AOT_550 nm	0.67	1.04	0.58
Angstrom 870/440	1.21	0.19	0.48
SSA_440 nm	0.88	0.88	0.88
SSA_675 nm	0.88	0.94	0.92
SSA_869 nm	0.88	0.96	0.94
SSA_1020 nm	0.89	0.96	0.95
REFR_440	1.48	1.57	1.51
REFR_675	1.51	1.57	1.55
REFR_869	1.52	1.56	1.55
REFR_1020	1.51	1.55	1.55
REFI_440	0.02	0.00	0.01
REFI_675	0.01	0.00	0.00
REFI_869	0.01	0.00	0.00
REFI_1020	0.01	0.00	0.00
ASYM_675	0.64	0.72	0.70
EffR_T	0.37	1.27	0.80
VolC_C	0.13	0.82	0.36
VolC_ F	0.08	0.04	0.04
No. of records	1923	207	995

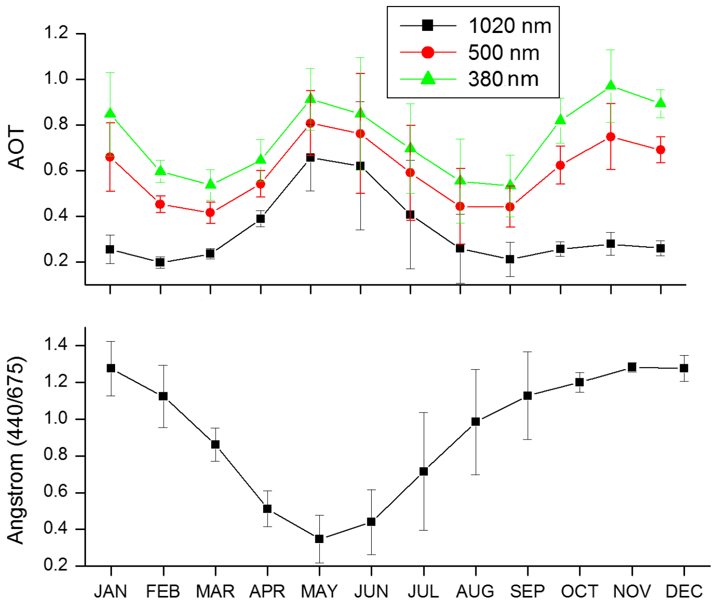

Figure 1. Monthly average AERONET (a) AOT and (b) Angstrom exponent over Kanpur. This figure is available in colour online at wileyonlinelibrary.com/journal/met

is less in comparison to that of relatively larger particles during the pre-monsoon season and during the monsoon months of June and July. The AOD value is low, around 0.2, in the other months and the atmosphere contains mainly small mode anthropogenic particles instead of those from natural sources. The insertion of the coarse mode aerosols due to the disturbed atmosphere and dry conditions during the summer is evident from the distribution pattern of 1020 nm optical depth and 440/675 nm Angstrom exponent over the station. In the winter, high values of Angstrom exponent and low AOD at the 1020 nm wavelength indicate the dominance of accumulation mode aerosols.

3.2. Comparison of Sunphotometer observations with MODIS data

The AERONET station data are compared with MODIS-derived monthly average AOD for a $1^{\circ} \times 1^{\circ}$ box around the station and the results are presented in Figure 2. From the satellite data, the highest AOD value, above 0.9, is detected during May to July. The station data agree well with satellite-derived data during October to April, but during May to September the satellite-estimated AOD shows higher values than those observed by the Sunphotometer. So, the satellite overestimates AOD during the summer monsoon months. These observations agree with the results described by Tripathi *et al.* (2005) that MODIS over-estimates AOD in pre-monsoon and monsoon seasons. However, a difference noticed from their findings is that during the post-monsoon and winter seasons, AOD values measured by the two instruments are almost the same. In the urban area, emissions from vehicular traffic, effluents from industries and other anthropogenic activities insert fine mode particles into the atmosphere (Derwent *et al.*, 1995). Kanpur is an industrialized and densely populated city with its own aerosol sources, so a combined effect of natural and anthropogenic aerosols results in high aerosol concentration over the station throughout the year.

A linear correlation coefficient analysis between daily satellite and station data for four seasons is carried out. It is observed that the correlations are high with values 0.844 during post

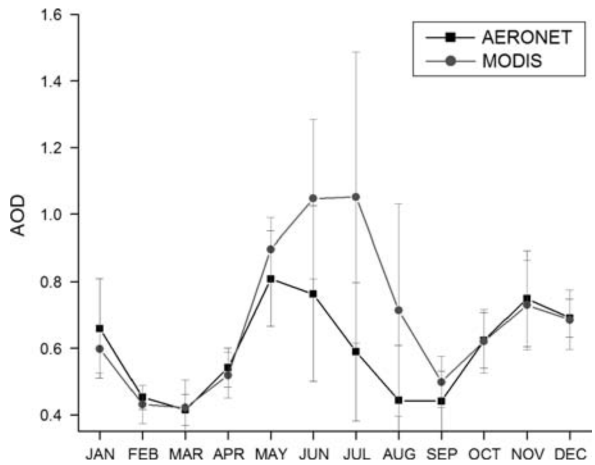

Figure 2. Comparison of AOD derived from MODIS and AERONET observations.

monsoon, 0.841 during pre-monsoon and 0.839 during winter at more than the 99% significance level. The correlation is at a minimum during the monsoon season (June to September) with a value of 0.738. It is evident that the satellite data disagree with the station data in maximum value during the monsoon season. The satellite sensor represents observations averaged over an area of $1^{\circ} \times 1^{\circ}$ around the station. The presence of clouds also disturbs the observations during the monsoon season. These are the possible reasons for the disagreement in observations taken by the two instruments during the monsoon season.

3.3. Circulation features and its effect on local aerosol properties

Local aerosol characteristics are influenced by transported aerosols from other locations through the circulation of the atmosphere. Air masses carry aerosol particles with them on advection from one place to another. Average wind patterns over India for different months of the year are shown in Figure 3.

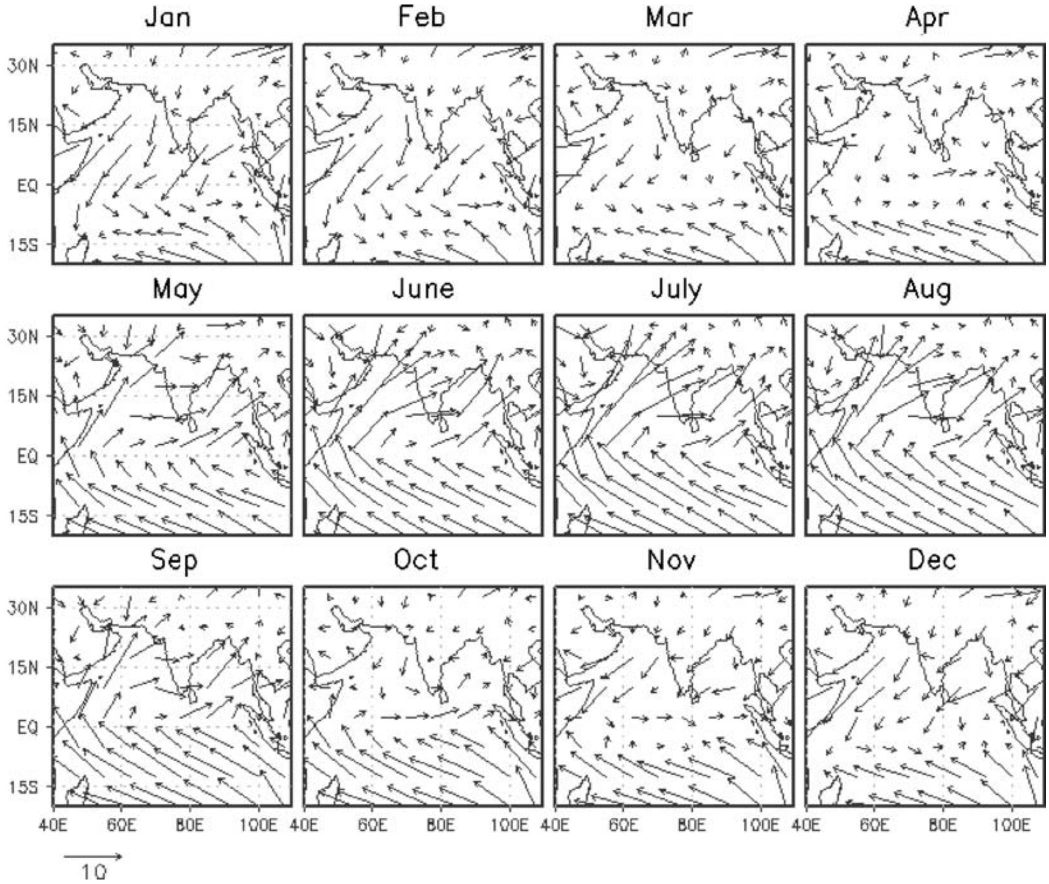

Figure 3. Average NCEP wind at 1000 hPa for different months.

Monthly mean wind analysis over the 1000 hPa level reveals the presence of strong winds over India and the surrounding oceans during May to September. The southwesterly winds are found to develop during May, become strong in the consecutive months and continue up to September. Strong winds of the order of 10–20 m s^{-1} are observed over the Indian region and surroundings during these months.

From September onwards the wind becomes weak over the north Indian plains. During October to April the wind is found to diverge from the region. This indicates that during these periods the possibility of occurrence of long-range transport of aerosols towards the station is low. On the other hand, the monsoon wind increases the production of marine aerosols over the northern Indian Ocean and Arabian Sea and the wind proceeding towards India carries these aerosols towards the subcontinent. The main component of marine aerosols is sea salt, which is hygroscopic. These particles combine with water vapour to form aerosols of coarse mode size. During the summer monsoon high aerosol loading is observed over the Arabian Sea due to the strong sea surface wind and transportation of dust particles from the deserts of Asia and Africa (Sivaprasad and Babu, 2012), so over the Arabian Sea a good amount of aerosol concentration is found during monsoon season. The wind proceeding towards India advects these particles towards the subcontinent.

Trajectory analysis has been done using the HYSPLIT model and some representative cases for Kanpur are shown in Figure 4. The model has been run 5 days backwards for altitudes of 100, 250 and 500 m. The trajectory is found to be almost the same for the three altitudes. The model-derived trajectory agrees well with the conclusions drawn from analysing the wind pattern. From the end of May to September, aerosols from the Arabian Sea and tropical Indian Ocean advect towards Kanpur. During October to April the trajectory pattern does not show any particular direction but originates from the regions to the north, northwest and east and does not cover as much distance as that observed during the monsoon. The possible contents in the transported air masses from northwest regions include the dust particles from the Thar Desert. The regions towards the north and northeast are covered with the Himalayas and they are not significant sources of aerosols, so transport from those regions does not influence the local aerosol properties much. In this case, the aerosols of local origin (mostly anthropogenic) are more important in the determination of aerosol properties over the station. From the variation in altitude (hPa) shown in the bottom panel of each figure, it is evident that during January air masses show a decrease in altitude on moving towards their destination. Particles are transported from the altitude ranging from 850 to 750 hPa through a gradually decreasing altitude track and reach the station within an altitude range 982 to 937 hPa. In March, the level shows a wavy nature in between 975 and 750 hPa, and in October the trajectory passes through almost the same altitude on its way towards Kanpur. However, in July the altitude increases as the air mass moves towards Kanpur. Here, the air mass advects from the surface of the Arabian Sea and it shows a gradual increase in height on moving towards its destination.

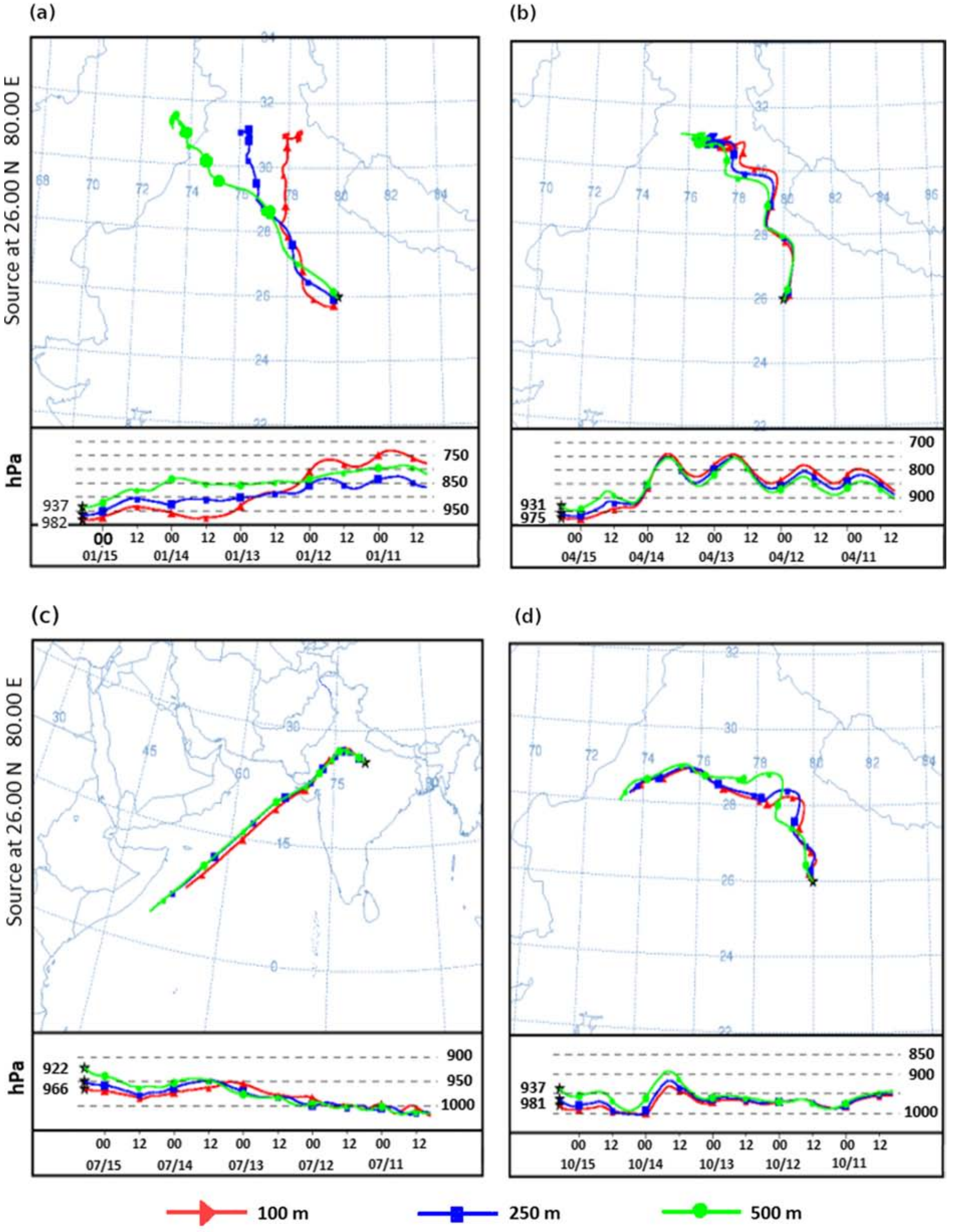

Figure 4. HYSPLIT backtrajectory for 5 days over Kanpur for (a) January (b) April (c) July and (d) October months of 2006 for three altitudes. This figure is available in colour online at wileyonlinelibrary.com/journal/met

3.4. Impact of dust storms associated with low pressure systems

The production of dust aerosols depends mainly on the surface winds, vegetation and soil moisture conditions. Regions with dry soil and less vegetation are potential sources of dust aerosols during high wind speed events. The global sources of dust aerosols are arid and semiarid desert areas from where the dust particles are lifted by surface winds (>5 m s^{-1}) and transported to other locations (Prospero *et al*., 2002; Washington *et al*., 2003). Many parts of the Indo-Gangetic plain often suffer dust storms during the pre-monsoon season (Middleton, 1986). The frequency of dust storms is at a maximum during the season over the northern and northwestern India and they are

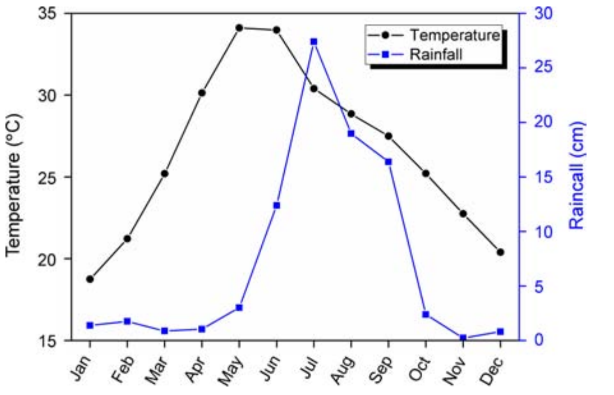

Figure 5. The variation of temperature and rainfall over Kanpur. This figure is available in colour online at wileyonlinelibrary.com/journal/met

transported by southwesterly summer winds from the Thar Desert in northwest India (Sikka, 1997).

The variation of mean (2001–2008) monthly temperature and rainfall pattern over the station is depicted in Figure 5. The highest temperature is observed at the city during May and June, reaching to around 35 °C. The temperature is about 30 °C during April and July. Heating of the ground generates unstable conditions over the station and convective low pressure systems develop. Along with the strong surface winds, these conditions give rise to the formation of dust storms. By the end of June, the monsoon sets in and rain continues up to the month of September. The region becomes wet during the season due to the rainfall associated with the monsoon. A maximum rainfall of around 27 cm is noticed in July. Rainfall is found to be above 15 cm during August and September. The low pressure systems induced by high temperature and dry conditions between April and June constitute favourable conditions for the formation of dust storms over Kanpur, while the wet soil conditions during the monsoon reduce the erosion of the soil even though the surface winds and temperature are high. According to Goudie and Middleton (2000), dust storm activities are common over the Ganga Basin during the summer months. Over Kanpur, maximum dust storm activity is reported in April, May and June. Dust storms also occur during the other months, however their frequency is negligibly small. Although the conditions are dry during the winter months the occurrence of dust storms is low due to high pressure conditions and the absence of strong winds. The low pressure system associated with dust storms enhances the production and lifting of natural dust aerosols. Thus, dust storms influence the aerosol properties over the station during hot and dry summer months.

3.5. Spectral dependence of aerosol optical depth

Size distribution of aerosol particles could be estimated from the spectral variation of aerosol optical depth. The present study analyses the spectral variation of AOD from the data derived at 1020, 500 and 380 nm wavelengths. Figure 1 shows that a high optical depth is observed at short wavelengths. This resembles the continental environment as described by Satheesh (1999). A rapid decrease in AOD is observed towards longer wavelengths over the station. This agrees with the arguments by Hoppel *et al.* (1990) and Moorthy and Satheesh (2000). The pattern of temporal variation of AOD is the same for the 380 and 500 nm wavelengths. However, it is slightly different in the 1020 nm observations for October to February, with a lower value compared to other wavelengths.

At 1020 nm, aerosol optical depth shows fewer values during October to March over Kanpur. This confirms an increase in concentration of coarse mode particles during April to November. At 500 nm, the AOD values do not fall below 0.4 at any time of the year. High values range from 0.6 to 0.8 in most of the months. Thus, accumulation mode aerosol concentration is found to be high during the entire year, as described earlier, with a maximum during the post monsoon months of October, November and December.

3.6. Classification of aerosols according to optical and microphysical properties

Data available at all points of observation are used for the cluster analysis. In an automated hierarchical clustering using Ward's method, the elbow or saturation is found at step 3122 and the number of clusters was identified to be three (3125 − 3122). Three clusters, depending on their properties, are depicted in Figure 6. Centroids of each parameter and the number of cases included in each cluster out of 3125 total data points are described in Table 1: 61.54% of the cases are included within cluster 1, 6.62% of the data points belong to cluster 2 and 31.84% of the cases come in cluster 3. The distance between the cluster centres is shown in Table 2. Clusters 1 and 2 are significantly different, with a distance of 1.59 between them. Cluster 3 is separated by the same extent to other clusters. Clusters 1 and 3 are also found to be dissimilar.

Here, clusters were identified on the basis of optical and microphysical properties and features of aerosol sources. The station is a polluted city situated in the Indo-Gangetic plane, so its atmosphere is vulnerable to pollution by aerosols from anthropogenic and natural sources. Dust storms over the station induce natural aerosol particles into atmosphere as described in Section 3.2. Human activities such as transport, industrial production, cooking and agricultural waste incineration inject different types of aerosol particles into atmosphere over the station. Taking into consideration these facts, classified clusters are defined as (1) urban fine aerosols, (2) heavy pollution, and, (3) urban mixed aerosols.

Cluster 1 consists of fine haze from human activities such as urbanization, biomass burning and industrial activities. This is the case where the maximum number of cases is included. Here, the volume concentration of fine mode aerosols is a maximum out of the three clusters. The effective radius is found to be a minimum for this type. Single Scattering Albedo (SSA) does not show a significant change with wavelength. The imaginary part of the refractive index indicates the partly absorbing nature of this type. Volume concentration of coarse mode is minimum and fine mode is maximum. Fine mode aerosols are formed by photochemical reactions and biogenic reactions and are predominant during low wind speeds, which is a favourable condition for the formation of these particles. The strength of this cluster indicates the dominant presence of urban fine aerosols over the station.

Table 2. Distance between final cluster centres.

Cluster	1	2	3
1	–	1.590	0.896
2	1.590	–	0.858
3	0.896	0.858	–

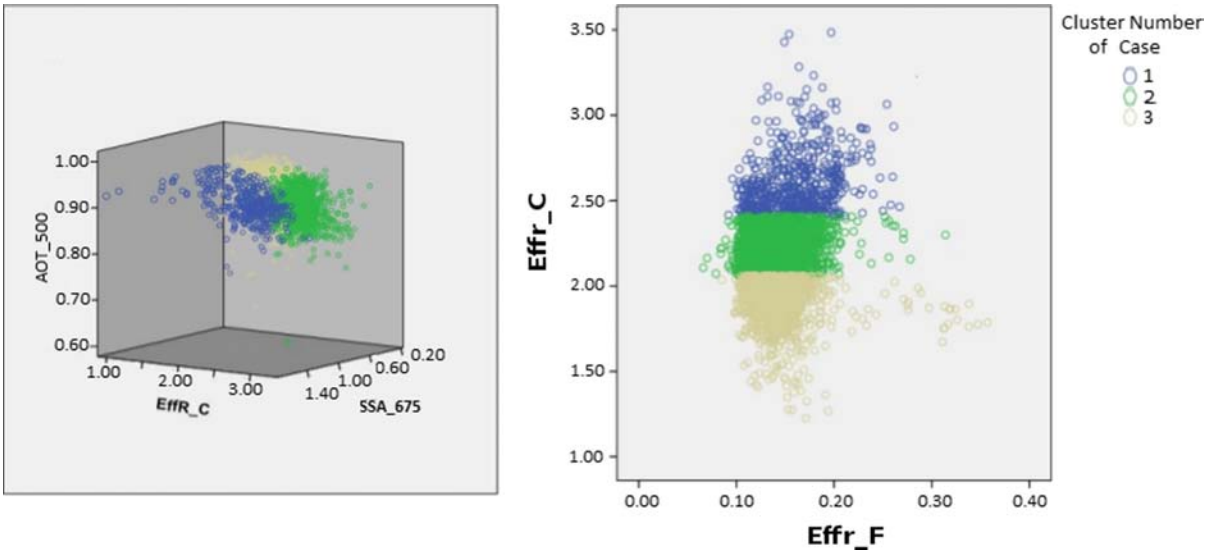

Figure 6. Three dimensional and two dimensional scatter plot using different parameters. This figure is available in colour online at wileyonlinelibrary.com/journal/met

Cluster 3 (urban mixed aerosols) shows the second largest number of occurrences. Coarse mode volume concentration and total effective radius show moderate values. The Angstrom exponent of 0.48 shows a relatively large particle size. This category forms as a result of mixing of different types of aerosols. Aerosols such as dust, sea-salt and black carbon are coated with fine mode aerosols such as sulphates and nitrates to form mixed type aerosols. Cluster 2 consists of the least number of data points, with only 6.62% of the total observations. This is the case when heavy pollution episodes take place over the station. Coarse mode aerosol concentration is highest in the cluster, which points to the fact that heavy pollution is caused by aerosols of great size. The highest effective radius and small Angstrom exponent values also suggest the presence of coarse mode particles. The refractive index and SSA indicate these particles are more scattering in nature compared to other clusters. Possible reasons for the occurrence of this case include dust particles originated by the dust events as described in Section 3.4. Dust particles coated with fine mode aerosols lead to the formation of coarse mode particles. Dust aerosols are put into the atmosphere by the action of wind on the soil surface and through other human activities. During the pre-monsoon season, air masses from the Thar Desert move towards Kanpur and act as a source for dust input into atmosphere of the station. Dust aerosols inserted into the atmosphere reduce atmospheric visibility. Fine mode aerosols are coated over dust particles so that the optical properties show a mixed pattern of these two.

4. Conclusions

The variability of aerosol properties shows that the north Indian station, Kanpur, is highly polluted by aerosols throughout the year. Coarse mode particles are found to contribute a high percentage to the total aerosol content during the summer months, whereas during winter and the post-monsoon seasons accumulation mode aerosols dominate over the station. The Angstrom exponent also shows the same dominance for coarse mode particles during summer. Spectral variation of aerosol optical depth agrees with the facts observed from the Angstrom exponent on the size distribution of aerosols. Aerosols are categorized into different groups through cluster analysis of different parameters and the presence of three major aerosol types were identified. They are defined according to their optical and microphysical property distribution over the station. Aerosol transport and dust storms have a significant role in the aerosol characteristics over the station besides the locally originated aerosol particles. The wind strength and trajectory play important role in the local aerosol properties by having impact in the formation of dust storms and the transport of particles from other regions.

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