

# Dust events and their influence on aerosol optical properties over Jaipur in Northwestern India

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**Abstract** In this study, we systematically document the link between dust episodes and local scale regional aerosol optical properties over Jaipur located in the vicinity of Thar Desert in the northwestern state of Rajasthan. The seasonal variation of AOT<sub>500 nm</sub> (aerosol optical thickness) shows high values ( $0.51 \pm 0.18$ ) during pre-monsoon (dust dominant) season while low values ( $0.36 \pm 0.14$ ) are exhibited during winter. The Ångström wavelength exponent has been found to exhibit low value ( $< 0.25$ ) indicating relative dominance of coarse-mode particles during pre-monsoon season. The AOT increased from 0.36 (April<sub>mean</sub>) to 0.575 (May–June<sub>mean</sub>).

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Consequently, volume concentration range increases from April through May–June followed by a sharp decline in July during the first active phase of the monsoon. Significantly high dust storms were observed over Jaipur as indicated by high values of single scattering albedo ( $SSA_{440 \text{ nm}}=0.89$ ,  $SSA_{675 \text{ nm}}=0.95$ ,  $SSA_{870 \text{ nm}}=0.97$ ,  $SSA_{1,020 \text{ nm}}=0.976$ ) than the previously reported values over IGP region sites. The larger SSA values (more scattering aerosol), especially at longer wavelengths, is due to the abundant dust loading, and is attributed to the measurement site's proximity to the Thar Desert. The mean and standard deviation in SSA and asymmetry parameter during pre-monsoon season over Jaipur is  $0.938 \pm 0.023$  and  $0.712 \pm 0.017$  at 675 nm wavelength, respectively. Back-trajectory air mass simulations suggest Thar Desert in northwestern India as the primary source of high aerosols dust loading over Jaipur region as well as contribution by long-range transport from the Arabian Peninsula and Middle East gulf regions, during pre-monsoon season.

**Keywords** Dust · Aerosols · Optical properties · Transport · Climate

## Abbreviations

AOT Aerosols optical thickness  
AE Ångström wavelength exponent  
AP Asymmetry parameter  
IGP Indo Gangetic plains  
SSA Single scattering albedo

## Introduction

Aerosols are important atmospheric constituents that interact with solar and terrestrial radiations and influence energy balance of the Earth–Atmosphere system. Ambient aerosols can directly modify the aerosol radiative forcing by scattering and absorption. The role of atmospheric aerosols, particularly the anthropogenic component, which contributes mostly to the accumulation mode fraction, is assuming increased importance, not only because of their potential health hazards, but also because of their potential to perturb the regional and global radiation balance and hence produce significant climate perturbations (Kaufman and Fraser 1997; Ramanathan et al. 2001). The radiative forcing of aerosols is strongly influenced by local variations in aerosols mass concentrations, size distributions and optical properties. Due to heterogeneous nature of aerosols, their impact on climate must be understood and quantified on regional scale, in addition to global scale. For this reason, the characterizations of aerosol properties in various regions around the globe are essential for the estimation of their climate impacts. Aerosol optical thickness (AOT) measured by Aerosol Robotic Network (AERONET) sites (Holben et al. 1998) around the globe offers measurements of aerosols over large domain of Asia including India as well. The ground-based radiometric and in situ observations over south Asia (Singh et al. 2004; Dey et al. 2004; Pant et al. 2006; Beegum et al. 2008; Pandithurai et al. 2008; Gautam et al. 2010, 2011; Soni et al. 2010; Bonasoni et al. 2010; Decesari et al. 2010; Gobbi et al. 2010; Ram et al. 2010) provided an insight into the strong seasonal variation of aerosol loading and the changes in aerosol properties over the Indo Gangetic plains (IGP) over India. A recent review on the observational and modeling studies over South Asia by Lawrence and Leliveld (2010) also provides an insight into the Asian atmospheric pollutant outflow and its large scale effects.

Particulate pollution is a widely spread phenomenon in southern Asia influencing climate and causing adverse health effects on humans. Mineral dust, transported by winds and convective motion over vast arid regions and deserts of western Asia and Eastern Africa, constitutes one of the major natural aerosol species over the Continental Tropical Convergence Zone (CTCZ) region during spring and summer (e.g., Chinnam et al. 2006; Nair et al. 2007). High aerosol loading, particularly dust has been observed by remote

sensing data (Prospero et al. 2002; Washington et al. 2003; Dey et al. 2004; Gautam et al. 2009; 2010) during the pre-monsoon season over the Gangetic basin in India. Very recently, a new insight into the mechanisms of aerosol transport from dust and pollution sources in central and southeastern Asia (Verma et al. 2008) to the Tibetan and Himalayan regions was provided by Huang et al. (2007) and Ramanathan et al. (2007). The Thar Desert centered in northwestern India and eastern Pakistan is among the primary dust source regions in the Indian subcontinent (Pease et al. 1998; Léon and Legrand 2003; Washington et al. 2003). The north, especially northwestern India, experiences maximum dust events during the pre-monsoon season, when dusts are transported by southwesterly summer winds from the western Thar Desert (Sikka 1997). The aforementioned ground-based campaign studies, however, are mostly based in the Gangetic–Himalayan region over India. The aerosol characterizations close to the sources of the atmospheric dusts such as arid and semiarid desert regions in India are very limited (Moorthy et al. 2007) and required for a better understanding for the variability of aerosol optical properties in relation to air mass origins during dust events.

Jaipur, the capital of Rajasthan (desert state) in northwestern India, experiences seasonal dust storms every year due to its location downwind of the Thar Desert. The dust storms are frequent and play a dominant role in climatology of the area. In the above context, continuous measurements under AERONET (Holben et al. 1998) of aerosol properties has been carried out at the campus of Birla Institute of Technology (BIT), Jaipur, since April 2009 located near the eastern edge of the Thar Desert. Enhanced pre-monsoon aerosol loading, comprising mineral dust and other anthropogenic carbonaceous and sulfate components, and associated radiative effects over northern India and the foothills/slopes of the Himalayas represent a potential aerosol–monsoon climate perturbation scenario (Lau et al. 2006; Lau and Kim 2006; Meehl et al. 2008; Wang et al. 2009; Gautam et al. 2009). Therefore aerosol measurements over Jaipur are very important to understand the variability of optical properties in vicinity of dust source region, particularly prior to the onset of Indian summer monsoon. In addition, information of aerosol optical properties near desert regions is of great importance to ascertain the aerosol scattering/absorbing

nature, especially due to the lack of measurements over northwestern India. Additionally, ground-based radiometric measurements at Jaipur also aid in the validation of aerosol products from satellite measurements that have shown to have relative biases and uncertainties over northern India (Kahn et al. 2009). The western and eastern regions of India are quite different in terms of aerosol optical/radiative properties as recently documented by radiometric and satellite observations from Gautam et al. (2011) and Dey and Girolamo 2011. The focus of our study is thus to characterize the dust events and transport which has been found to affect regional aerosols optical properties and radiative estimates (Dey and Girolamo 2011).

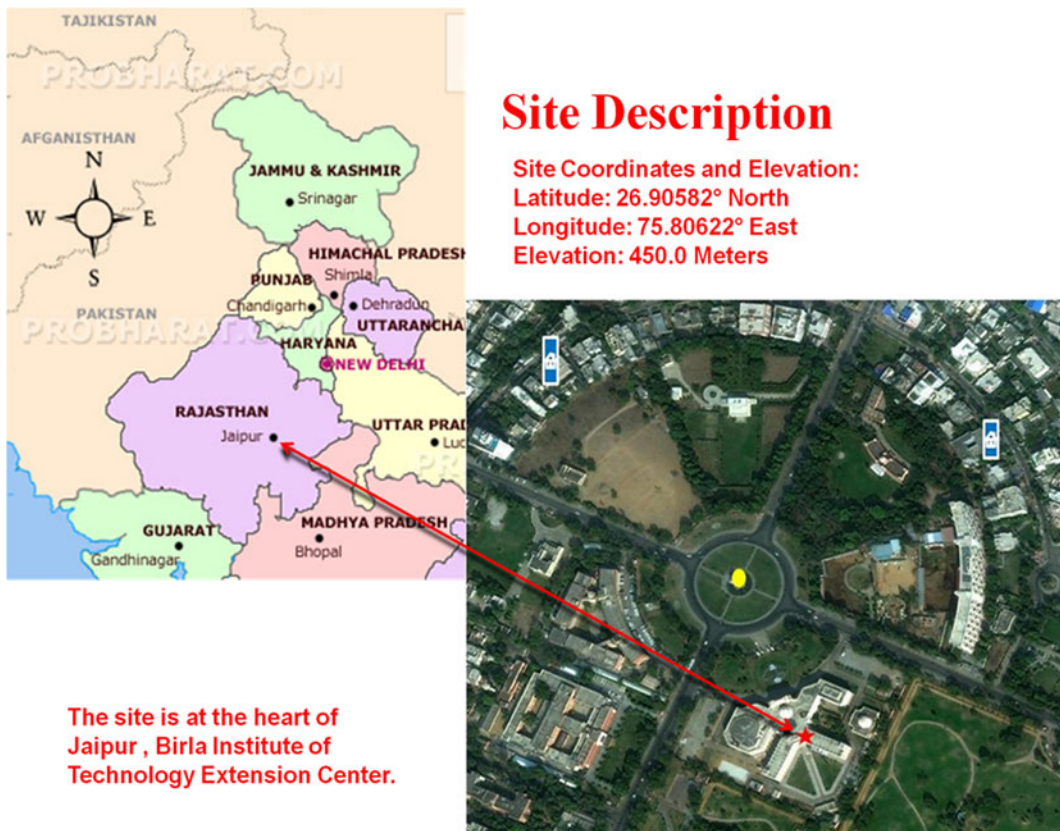
The study documents the variations in aerosols optical properties on diurnal and seasonal time scales from sun photometer data over cloud-free days, with a focus to pre-monsoon season (during May and June) in 2009 and 2010 and examines

the aerosol characteristics in details during the dust episodes. During the study, four intense dust events were observed in 2009 on 5, 11 May and 18, 19 June, and four more dust events were observed in 2010 on 14, 15 May and 22, 27 June. Efforts have been made in this study to explore regional aerosol characteristics and their origins using the AERONET data and air mass trajectory simulations during dust events.

### Site and instrument description

#### Sampling platform and instrumentation

In this study, we use the Version 2 retrievals of aerosol properties from a CIMEL sun photometer over BIT Jaipur campus in Rajasthan, which is part of the AERONET project (Holben et al. 1998). The CIMEL sun photometer is located on a metal tower



**Fig. 1** The map showing location of the Jaipur and Thar Desert along with AERONET Sun-sky radiometers (marked as red star) utilized in the study. Blue marks represent prime city location

(6 ft high) at the roof top at BIT campus (Fig. 1) with no obstructions to the sun. The CIMEL sun photometer takes measurements of the direct sun and diffuse sky radiance with  $1.2^\circ$  full field of view within the spectral range 340–1020 nm (Holben et al. 1998). The direct sun measurements were made at eight spectral channels (340, 380, 440, 500, 675, 870, 940, and 1020 nm) with triplet observations per wavelength and sky radiance measurements at four spectral channels (440, 675, 870, and 1020 nm). This data set is in the form of Level 2.0 quality assured product after cloud screening and necessary post calibration. The AOT is retrieved at all channels (Holben et al. 1998) other than the 940-nm channel, which is used to retrieve atmospheric water vapor content. The CIMEL sky radiance measurements together with the direct sun measurements of optical depths are used to retrieve optical equivalent aerosol size distributions and refractive indices and hence deduce the spectral dependence of SSA. Version 2 retrievals utilize the enhancements described by Dubovik et al. (2006) over the Version 1 algorithm of Dubovik and King (2000). The measured data was saved nearly 15-min averages. Outliers and periods with obvious instrument malfunction were removed from this data during the Level-2 production. The data were then averaged on an hourly basis with the condition that each hour consisted of more than 30 min of data.

#### Station overview

The measurement site is located at Jaipur (26.81°N, 75.48°E), the capital of Rajasthan state (Fig. 1). The city of Jaipur, which is in the vicinity of the Thar Desert,

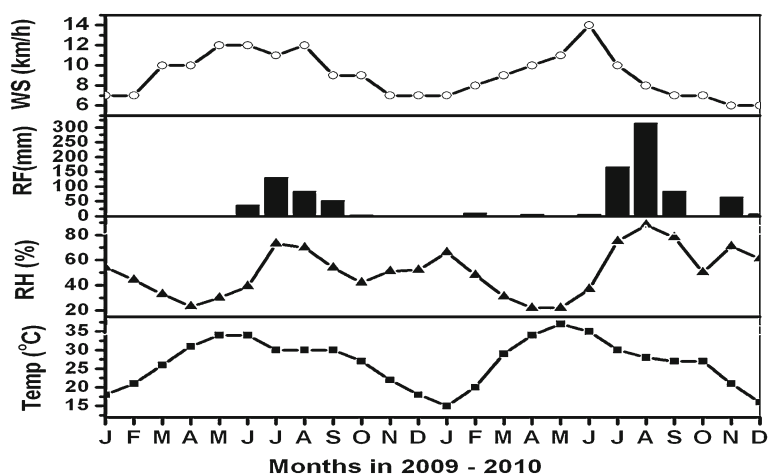
experiences a semi-arid climate with medium rainfall (60 cm). More specifically, Jaipur is near the eastern edge of the Thar Desert. The population growth rate under the urbanization is quite high (53.09%) in the last decade. Located near the Aravali mountain ranges at an altitude of 431 m AMSL, Jaipur is surrounded by hills to the north and the east. There are small-scale industries in Jaipur, and some of the major ones are located to the west and south of the city about 15–40 km from the site location. New Delhi, the capital of India, is 230 km away in the northeast direction.

Figure 1 shows the location of the AERONET sun photometer. The site is located in the campus of the BIT in the central part of Jaipur. The BIT Jaipur campus is about 3 km away from the center of Jaipur City. The site is considered relatively free from local perturbations; hence, it represents more regional characteristics than local nature.

#### Synoptic meteorology

A clear seasonal pattern of weather is seen from the ambient meteorological parameters obtained from the wunderground site for 2009 and 2010 <http://www.wunderground.com/global/stations/42348.html>. The meteorological parameters are presented in Fig. 2. The average temperatures were high during the summer season in April through June with an average monthly value ranging from 31°C to 37°C. The highest temperature, however, reached 48°C on 14 June, 2010. Diurnal temperature gradient is found to be much higher during the pre-monsoon season. During the winter, the coldest nights reached below 3°C on 11 January 2010. The highest average relative humidity (RH) took

**Fig. 2** Averaged monthly temperature (°C), relative humidity (%), rainfall (mm) and wind speed (km/h) over study location



place in August 2010 (rainy season). RH exhibits two maxima, one during monsoon and other is observed in January (in winter). The highest difference between the maximum and minimum RH took place during the pre-monsoon season due to high diurnal variation of the temperature. The wind speeds generally follows the temperature trend over the location. Daytime exhibited the highest wind speeds. The prevailing wind direction during May–June remains between 200° and 230° (southwest).

**Results and discussions**

**Aerosol optical properties**

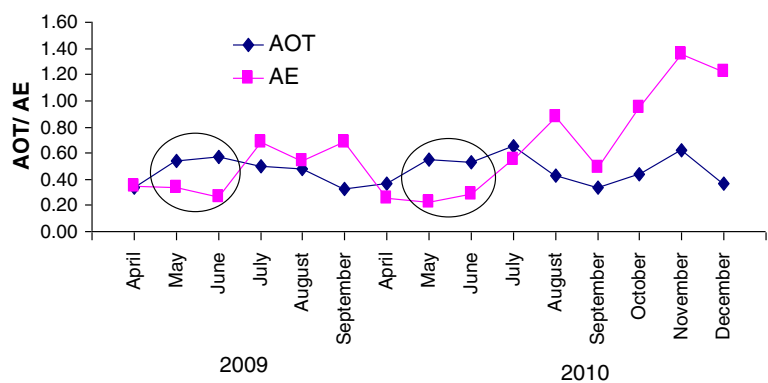
The variability of monthly average AOT at 500-nm wavelength ( $AOT_{500\text{ nm}}$ ) and the Ångström exponent ( $\alpha$ ) at 440–870 nm over Jaipur from April 2009 are shown in Fig. 3. The  $AOT_{500\text{ nm}}$  over the region remains mostly higher than 0.33 throughout the year. A systematic pattern strongly influenced by the seasonal variability is observed in the spectral variations of aerosol loading during both years. AOT generated mainly by coarser particles are characterized by  $\alpha < 0.25$ , which is deduced from a multispectral log-linear fit to the classical equation of Ångström (Ångström 1964) in the wavelength range 440–870 nm. Higher value of  $\alpha$  indicates dominance of fine-mode particles with higher spectral variation in AOT. A high aerosol loading has been observed during May and June (pre-monsoon seasons) with average AOT  $> 0.54$  corresponding to the maximum decrease in  $\alpha$  value. The large variation in temperature and scanty rainfall for a prolonged period cause weathering of the soil and the loose dust is picked by the winds as they grow

stronger (Moorthy et al. 2007). During the other seasons,  $AOT_{500\text{ nm}}$  is variable with  $\alpha$  higher than 0.5. The contrast between the highest AOT and the lowest mean Ångström exponent (negative and zero values) was observed during the pre-monsoon season, indicating a relatively high ratio of large particles to small particles due to dust loading in this season. The notable decrease in  $\alpha$  during pre-monsoon season at the site indicates an abundance of coarse particles arising because of the dust loading, which will be explored in subsequent sections.

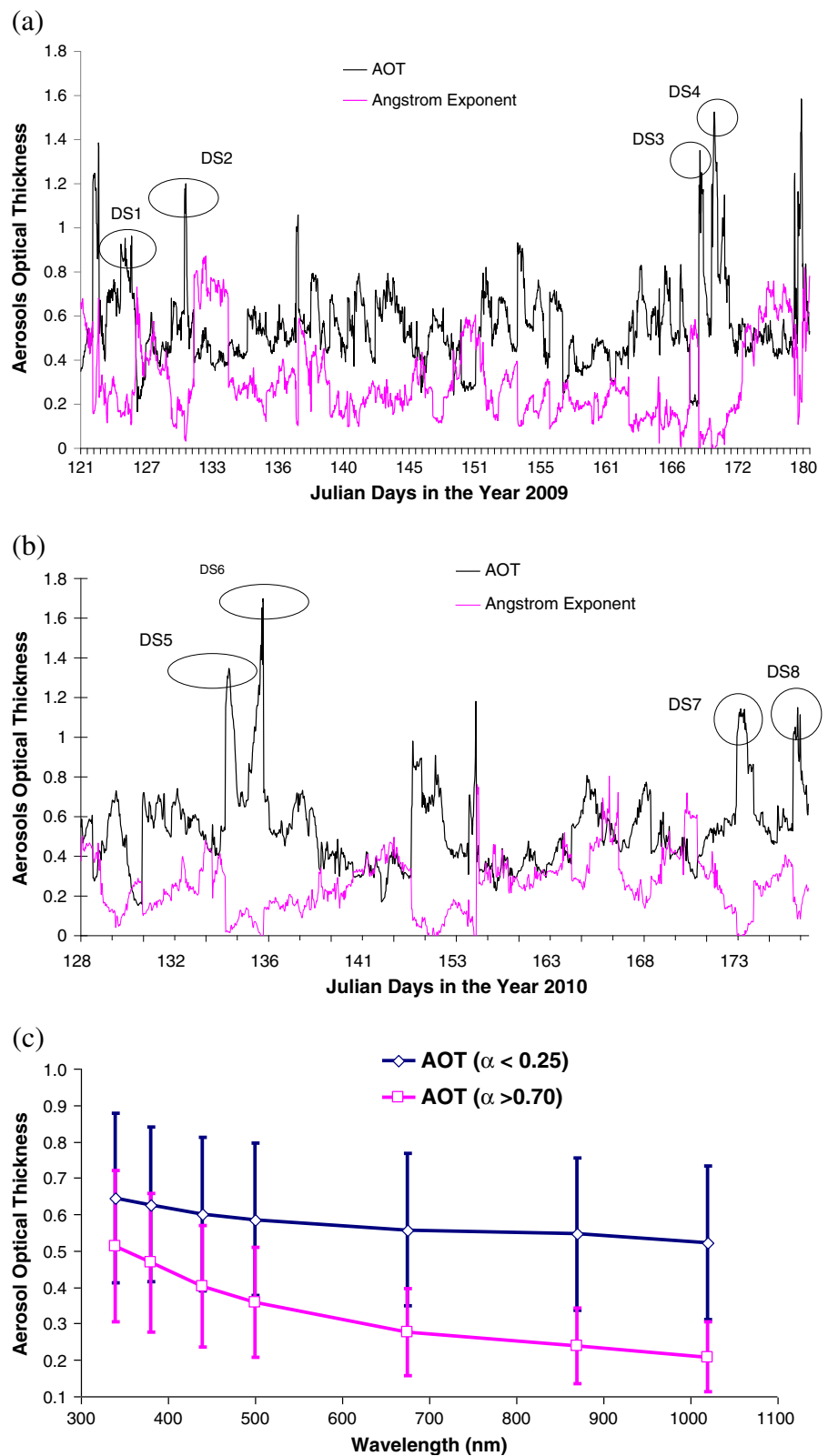
**Identification of dust events**

The aerosol optical and microphysical properties during dust events over Jaipur observed during May and June 2009 and 2010 are studied in the subsequent sections. Figure 4a,b displays the time series of the  $AOT_{500\text{ nm}}$  and  $\alpha$  for May and June 2009 and 2010, respectively derived from all AERONET data. During the two pre-monsoon periods, 8 dust events were identified, marked as “DS#” in Fig. 4a,b. To quantitatively distinguish dust storm from the low dust loading background conditions the relatively high aerosol loading days that lasted for more than 3 hr together with a significant drop in Ångström exponents ( $\alpha$ ) are only considered, i.e., if  $\alpha$  effectively remains less than 0.25 with a dominance in high AOT values (Sabbah et al. 2001; El-Askari et al. 2009). Table 1 lists the dust events and the corresponding meteorological parameters. The starting and ending time of the events was also defined by the behavior of the AOT and  $\alpha$  value. The former indicates the period from which  $\alpha$  started to decrease significantly and the latter at which  $\alpha$  increased to the values prior to the events or the average AOT level in 2009–2010. Most of the events took place in the early morning,

**Fig. 3** Seasonal variations in aerosol optical thickness (AOT) at 500-nm wavelength and Ångström exponent (AE) at 440–870 nm over Jaipur



**Fig. 4** Time series in aerosol optical thickness (*AOT*) at 500-nm wavelength *AOT*<sub>500</sub> and Ångström exponent (*AE*) at 440–870 nm over Jaipur during May and June as shown in Julian days (a), 2009, (b) 2010, (c) spectral *AOT* variations for pre-monsoon season for two groups of low and high  $\alpha$  values, i.e.,  $\alpha < 0.25$  and  $\alpha > 0.70$  averaged for 2009–2010



**Table 1** Dust events and the corresponding meteorological parameters

Days (DS#)	Aerosol optical thickness (AOT) at 550 nm		Angstrom exponent 440–870 nm (AE)		Temperature °C			Relative humidity (RH) (%)	Wind speed (WS) (km/h)
	AOT Max	AOT Min	AE Max	AE Min	Temp max	Temp min	Temp average	RH average	WS max
5/4/09	0.7635 (10:09)	0.6002 (13:39)	0.3256 (09:39)	0.1641 (17:27)	40	28	34	18	22
5/5/09 (DS1)	0.9607 (14:54)	0.7084 (12:24)	0.2459 (09:39)	0.1074 (14:24)	39	27	32	27	28
5/6/09	0.7545 (06:43)	0.1678 (11:39)	0.7283 (09:39)	0.2399 (07:14)	38	26	33	22	13
5/10/06	0.6257 (17:36)	0.4905 (14:54)	0.2913 (11:24)	0.1458 (16:09)	42	26	35	22	37
5/11/09 (DS2)	1.1992 (07:31)	0.4539 (15:54)	0.2153 (18:01)	0.0329 (07:31)	38	26	32	44	30
5/12/09	0.5461 (15:09)	0.3876 (06:46)	0.8720 (15:38)	0.6318 (09:24)	39	27	33	30	17
6/17/09	0.2437 (14:28)	0.1907 (15:43)	0.5840 (14:28)	0.4477 (17:30)	37	23	32	34	18
6/18/09 (DS3)	1.3498 (13:58)	0.8862 (10:28)	0.0745 (17:10)	-0.0346 (13:58)	38	28	34	30	17
6/19/09 (DS4)	1.5243 (16:56)	0.5073 (08:58)	0.1365 (09:43)	-0.022 (16:43)	41	30	35	26	19
6/20/09	1.1437 (09:58)	0.6625 (13:13)	0.1698 (15:58)	0.0186 (09:58)	42	30	35	24	31
5/13/10	0.5577 (12:39)	0.4034 (14:54)	0.4787 (08:39)	0.1966 (12:39)	43	30	36	12	28
5/14/10 (DS5)	1.3459 (07:22)	0.6489 (17:25)	0.1403 (17:44)	0.0156 (07:39)	43	33	37	13	19
5/15/10 (DS6)	1.6802 (14:39)	0.6601 (18:03)	0.1440 (17:32)	-0.0393 (13:09)	42	33	38	13	17
5/16/10	0.5768 (12:39)	0.4527 (14:09)	0.2881 (16:58)	0.1232 (13:54)	43	30	38	15	20
6/21/10	0.6578 (15:29)	0.5536 (08:29)	0.1575 (08:29)	0.1098 (09:59)	44	34	39	20	26
6/22/10 (DS7)	1.1418 (12:59)	0.8196 (17:11)	0.0735 (18:17)	-0.0099 (12:59)	42	33	38	21	33
6/23/10	0.6223 (13:59)	0.4598 (17:59)	0.3115 (18:18)	0.1988 (13:29)	41	32	37	30	28
6/27/10 (DS8)	1.1479 (15:15)	0.8772 (15:45)	0.1958 (09:45)	0.084 (16:30)	42	32	38	31	24
6/28/10	0.8641 (14:30)	0.7848 (15:45)	0.3619 (16:00)	0.1141 (14:30)	42	25	36	39	31

particularly, their starting times observed between 0630 and 1030 hours (local time). Dust events mostly ended in the same day, except the event DS5. The event DS5 (14 May 2010) lasted for the longest duration of about 2 days. The dust event with a longer duration time is expected to have a stronger effect on the urban air quality and human health. The daily AOT data (Fig. 4a) shows large episodic dust storms. As shown in Table 1, the maximum wind speeds during the events in most cases were higher than 17 kmh<sup>-1</sup> and the prevailing wind direction mostly remains southwesterly associated with the pre-monsoon to monsoon onset conditions. Figure 4 indicates that there might be a dust storm on 122 days in 2009 (i.e., 2 May). However, higher AOT was observed with a relatively higher  $\alpha$  value, suggesting a fine-mode contribution. Thus, this event is not taken into account. The effect of dust events on aerosol optical properties is discussed in [Optical and microphysical properties of aerosols](#).

Optical and microphysical properties of aerosols

*Aerosol spectrum and Ångström parameter*

Figure 4 shows the variation of AOT<sub>500 nm</sub> for a total eight identified events labeled as DS1 to DS8: 4 selected days in 2009 (May 5, 11 and June 18, 19 in 2009; Fig. 4a) and four selected days in 2010 (May 14, 15 and June 22, 27 in 2010; Fig. 4b). AOT<sub>500 nm</sub> shows large variability from 0.15 to 1.68 during the months of May and June. It is evident from Fig. 4a that during the dust events, relatively strong AOTs are observed, e.g., during DS1 and DS2, AOT<sub>500 nm</sub> has been observed to be 0.95 and 1.2, whereas in DS3–DS8, values greater than 1.2 are observed with the highest value reaching 1.68, which was reported during DS6.

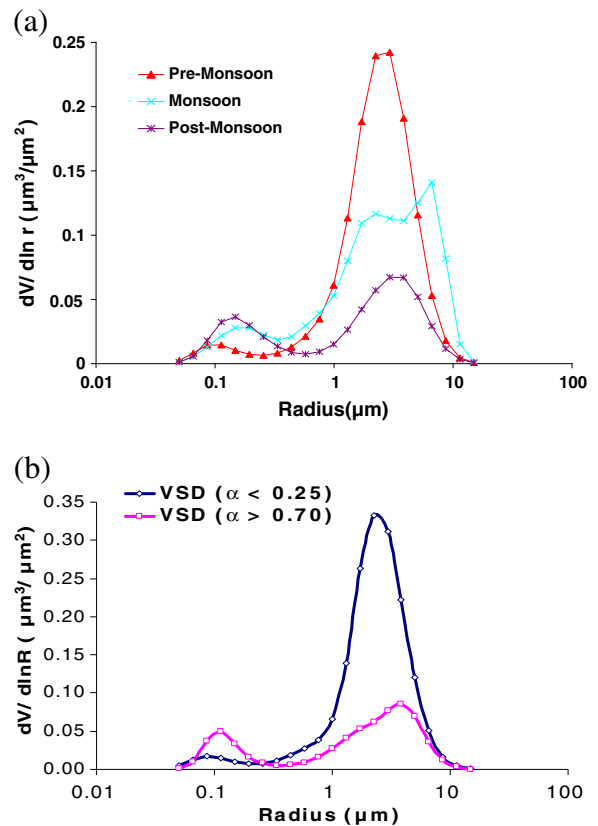
Dey et al. (2004) showed that dust days were associated with relatively higher AOT values than non-dust event days at Kanpur over IGP region in India. A similar phenomenon is also observed at the present

site in Jaipur, revealing high  $AOT_{500}$  values of  $>1$  during the dust events in June. Prior to the dust event day,  $\alpha$  (computed for the entire wavelength range from 0.34 to 1.02  $\mu\text{m}$ ) was found to be higher compared to that during dust storms. During the DS6 event, AOT was observed to increase above 1.5, and  $\alpha$  was found to decrease to  $-0.0012$ . All dust events contribute to an increase in AOT by 60–90 % and decrease in  $\alpha$  by 80–90 %. The maximum AOT associated with minimum  $\alpha$  has also been reported at Indo-Gangetic (IG) plains in India (Prasad and Singh 2007; Tanre et al. 2003; Dey et al. 2004). Long-range transport of dust from the Arabian Peninsula also contributes to the net regional aerosol loading with marked increase in AOT over the northern Arabian Sea in May–June relative to April (Gautam et al. 2010). Shipborne measurements over the Arabian Sea have also indicated enhanced dust loading during pre-monsoon season, particularly over the northern open sea regions (Satheesh et al. 2006; Kaskaoutis et al. 2010).

In addition to the strong dust events and their influence on aerosol optical property variations, we further separated the background aerosol loading (non-dust) conditions from typical dusty conditions over Jaipur by separating the AOT retrievals into two groups of low and high  $\alpha$  values, i.e.,  $\alpha < 0.25$  and  $\alpha > 0.7$ , during the pre-monsoon season in 2009–2010. This separation allows us to comment on relatively higher coarse mode influence relative to the background anthropogenic emissions since coarse particles such as mineral dust cause enhanced solar extinction at near- and shortwave-infrared wavelengths compared to fine particles. Figure 4c shows the spectral AOT distribution for these two groups. Relatively small change in AOT values are observed with a declining slope at increasing wavelengths, i.e.,  $AOT_{340\text{ nm}}=0.65$  to  $AOT_{1,020\text{ nm}}=0.52$  in greater dust loading conditions ( $\alpha < 0.25$ ), while low AOT ( $< 0.3$ ) values are observed for  $\alpha > 0.7$  with a declining steep slope at increasing wavelengths in background aerosol SSA spectra. The results clearly indicate a major fraction of high aerosol optical depths ( $> 0.5$ ) associated under greater dust loading conditions.

#### Aerosols volume size distribution

The dominance of the particles with size range  $> 2\ \mu\text{m}$  is clearly evident in Fig. 5a during the pre-monsoon season, which implies that volume concentration in the coarse mode is much higher than that of the fine mode



**Fig. 5** Aerosol volume size distribution over Jaipur: **a** seasonal variations during 2009–2010; **b** for two groups of low and high  $\alpha$  values, i.e.,  $\alpha < 0.25$  and  $\alpha > 0.7$ , during pre-monsoon season averaged for 2009–2010

during pre-monsoon seasons over the region. This type of bi-modal lognormal aerosol size distribution peaking in the coarse mode during pre-monsoon period is characteristic in northwestern India and the Indo-Gangetic Plains (Gautam et al. 2011). The dust storms lead to large increases in the volume concentration at the coarse mode. As a result, the total particle volume concentration at the coarse mode is increased by 70 % relative to fine mode particles. It is interesting to note a peak at  $0.14\ \mu\text{m}^3\ \mu\text{m}^{-2}$  at  $10\ \mu\text{m}$  radius (lower volume concentration than the dominating mode) during monsoon seasons, which may be associated with the hygroscopic growth of small particles in the presence of high RH (Parameswaran and Vijayakumar 1994; Kotchenruther et al. 1999). The volume concentration at the fine mode, however, remains very low — in the range of  $0.05\ \mu\text{m}^3\ \mu\text{m}^{-2}$  centered at the  $0.1\text{-}\mu\text{m}$  radius. The result implies that the AERONET site at Jaipur is mainly affected by the coarse-mode particles during pre-



monsoon season. Like monthly averaged AOT, volume concentration for May–June period also indicate a progressive build up of aerosols loading in April that peaks in May–June, and is followed by a decline in July, August and September consistent with the retreat of the monsoon. This aerosol build up and the decline in the second half of the monsoon is explained by the strengthening and decay phases of the low level westerly flow (Lau et al. 2006).

In addition, size distribution variation at low and high  $\alpha$  values i.e.,  $\alpha < 0.25$  and  $\alpha > 0.7$  from the 2009–2010 pre-monsoon period are shown in Fig. 5b. Low volume size distributions ( $< 0.12 \mu\text{m}^3 \mu\text{m}^{-2}$ ) are observed in both coarse and fine mode fractions with background aerosols condition. However, coarse mode fraction dominance is found to be associated with greater dust loading conditions with relatively higher volume size distribution ( $0.35 \mu\text{m}^3 \mu\text{m}^{-2}$ ).

## Radiative properties of aerosols

### *Single scattering albedo*

Figure 6 shows the daily variations in single scattering albedo (SSA) at four wavelengths (440, 675, 870 and 1020 nm) during four dust storms cases, i.e., DS1, DS2 (Fig. 6a) and DS3, DS4 (Fig. 6b) over Jaipur. The SSA represents the scattering of solar radiation attenuation by particulate in the polluted environment. The details of retrieval of SSA from sun and sky radiance measurements by CIMEL sun photometer are discussed by Dubovik and King (2000).

Wavelength dependency of SSA with higher values ( $> 0.9$ ) in the near-infrared range compared to lower values at shorter wavelengths (especially at 440 nm associated with enhanced absorption of iron oxide within dust particulates) indicates the dominance of high dust loading. The average values of SSA at 675–1,020 nm wavelength are found to be 0.948 and 0.953 during May 2009 and 2010, respectively, indicating that the period is dominated largely by the presence of scattering aerosols. The dominance of dust is clearly seen (Fig. 6a) in spectral properties with SSA at 440 nm ( $\text{SSA}_{440 \text{ nm}}$ ) being the lowest (absorbing) to increasing values at longer wavelengths (scattering), i.e.,  $\text{SSA}_{440 \text{ nm}} = 0.88$  and  $\text{SSA}_{1,020 \text{ nm}} = 0.97$  during DS1. SSA spectra in our study period also exhibit strong spectral variation, with

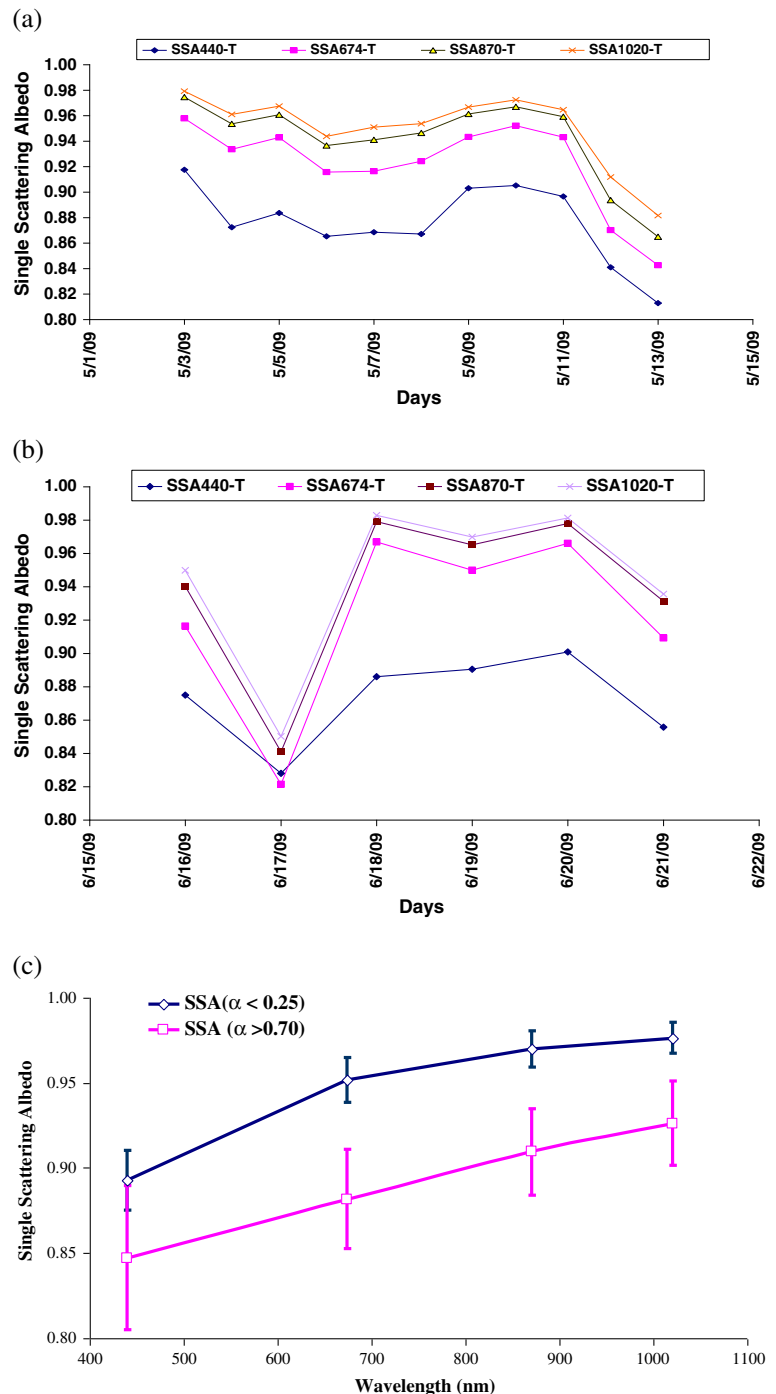
the higher values at the higher wavelengths for dust loading conditions similar to previous studies over northern India (Dey et al. 2004; Prasad and Singh 2007; Pandithurai et al. 2008; Ganguly et al. 2009; Gautam et al. 2011). The slope of SSA spectra has been found to be reduced in the non-dust event days in accordance with the AOT spectrum. The DS1 and DS2 (Fig. 6a) show small increase of  $\text{SSA}_{675 \text{ nm}}$  from 0.93 to 0.94, while a maximum increase in  $\text{SSA}_{675 \text{ nm}}$  from 0.82 to 0.96 has been associated with the strongest event on DS3 and DS4 (Fig. 6b). Dust SSA spectra is expected to follow a positive slope and negative curvature, whereas urban industrial and biomass smoke SSA spectra have negative slope (Russell et al. 2010). Thus increase in SSA is due to the abundant dust loading in the region, attributing to the scattering state of the atmosphere. The changing nature of SSA spectra during these events indicates a strong impact on the optical properties. Similar to the separation of aerosol size distribution of dusty atmosphere relative to background aerosol loading, the SSA retrievals are also divided into two groups of high and low  $\alpha$  values, i.e.,  $\alpha < 0.25$  and  $\alpha > 0.7$ .

Figure 6c shows the SSA spectral variations for the low and high  $\alpha$  values, i.e.,  $\alpha < 0.25$  and  $\alpha > 0.7$ . The spectral shape exhibit a steep spectrum of increasing SSA values with increasing wavelengths for greater dust loading conditions while a relatively less pronounced SSA spectrum is found in case of background aerosols condition. Lower SSA at shorter wavelengths, i.e.,  $\text{SSA}_{440 \text{ nm}} = 0.89$  and relatively higher values at longer wavelengths  $\text{SSA}_{1,020 \text{ nm}} = 0.976$  indicate high dust loading over the region.

### *Asymmetry parameter*

The angular distribution of light scattering by the aerosol particles is defined by the asymmetry parameter (AP). AP provides information on the aerosol radiative forcing and depends on the size and the composition of particles (Andrews et al. 2006). The AP value ranges from  $-1$  (for entirely backscattered radiation) to  $+1$  (for entirely forward-scattered radiation) for ideal case. The monthly mean values of AP during April–June retrieved by sun/sky radiometer at 675 nm are being compared for the present study site

**Fig. 6** Daily averaged single scattering albedo (SSA) at four wavelengths (440, 675, 870 and 1,020 nm) during the dust storms on **a** May 5 and 11, 2009 (DS1, DS2) and **b** June 18 and 19, 2009 (DS3, DS4), respectively; **c** spectral SSA variations averaged for pre-monsoon season for 2009–2010 for two groups of low and high  $\alpha$  values, i.e.,  $\alpha < 0.25$  and  $\alpha > 0.7$



with two other sites, i.e., Kanpur and Gandhi College (Srivastava et al. 2011) in Table 2 over Jaipur.

Our result for AP shows a negative correlation with the AE (Table 2). The result indicates a decrease in the magnitude of AP with increasing AE values, and vice versa, at all the stations during pre-monsoon period. A

distinct decrease is evident in AE values over Jaipur region than reported at other two stations indicating clear dominance of dry coarse-size particles over the region. The spectral variations of AP at four discrete wavelengths during pre-monsoon period for 2009 also indicate a decrease in AP magnitude with increasing

**Table 2** Comparison of aerosol parameters at Jaipur to two other sites over IGP region

Months (2009)	Locations		Mean aerosol parameter		
	AOT <sub>500 nm</sub>		AE <sub>440–870 nm</sub>	SSA <sub>675 nm</sub>	AP <sub>675 nm</sub>
May	Jaipur	0.56 (±0.16)	0.32 (±0.15)	0.93 (±0.02)	0.71 (±0.02)
	Kanpur	0.65 (±0.12)	0.74 (±0.27)	0.91 (±0.03)	0.68 (±0.02)
	Gandhi College	0.67 (±0.20)	0.91 (±0.34)	0.89 (±0.02)	0.67 (±0.02)
June	Jaipur	0.59 (±0.21)	0.29 (±0.19)	0.95 (±0.01)	0.72 (±0.01)
	Kanpur	0.69 (±0.24)	0.45 (±0.27)	0.94 (±0.03)	0.70 (±0.02)
	Gandhi College	0.77 (±0.34)	0.71 (±0.33)	0.92 (±0.03)	0.69 (±0.02)

wavelength in the visible region and an increase in the near-IR region for all the dust events and period. This decrease in AP further confirms our result for the presence of coarse-size dust particles during the high AOT days.

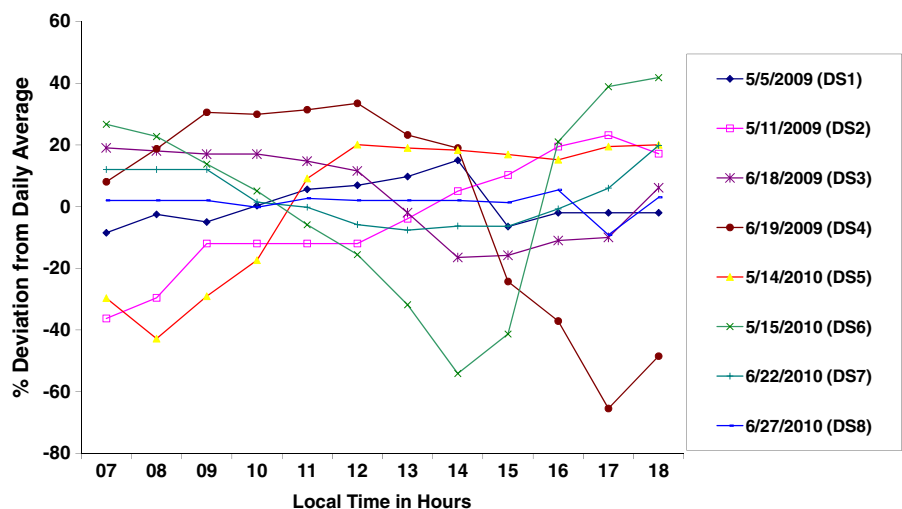
Diurnal variation of AOT<sub>500 nm</sub>

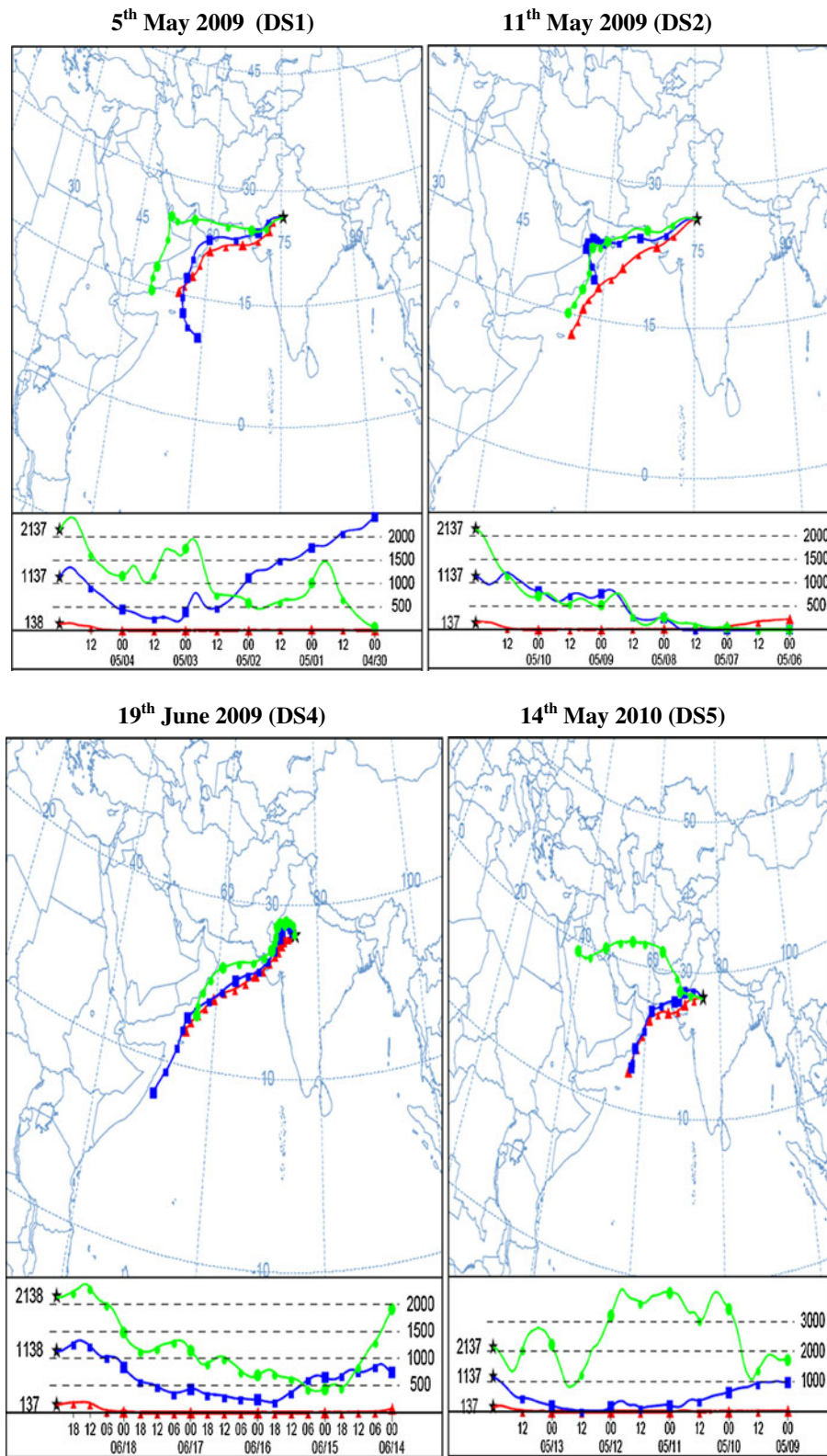
The percentage departure from the daily average in Fig. 7 depicts the diurnal variations of AOT<sub>500 nm</sub> averaged for all the dust storms events in 2009–2010. The maximum diurnal variations have been observed in the morning and afternoon during pre-monsoon season. Similar diurnal variation behavior has been observed where dust has been found to be a major contributor of AOT (Smirnov et al. 2002). Most dust events started early in the day, usually between 0700 and 0900 hours, as indicated in Fig. 7. The maximum departure in AOT is observed between

1300 and 1700 hours, while in the case of DS1, DS2 and DS5 events, maximum departure is observed before 1000 hours local time.

The local diurnal cycle of aerosol loading and the seasonal variations of the aerosol are found to show a significant dependence on the ambient meteorological conditions (namely, temperature, RH, and wind speed) (Table 1). The average temperature variations are quite strong during the study period which causes the enhancement of the local diurnal cycle. The huge loading of long-range dust transport completely surpasses other pollution sources during dust storm days. The high diurnal variation over the site is mainly caused by the dust aerosols entrained into the mixed layer as the influence of local pollutants seems to be not much dominant over the site. The RH is generally observed to be decreased after the dust events. Wind speed has been found to be greater than 17 kmh<sup>-1</sup> during all dust event days.

**Fig. 7** Percentage departure of AOT<sub>500 nm</sub> from daily average for dust storm events in 2009–2010





**Fig. 8** Five-day back trajectories starting from dust events day at 500, 1,500, and 2,500 m AMSL

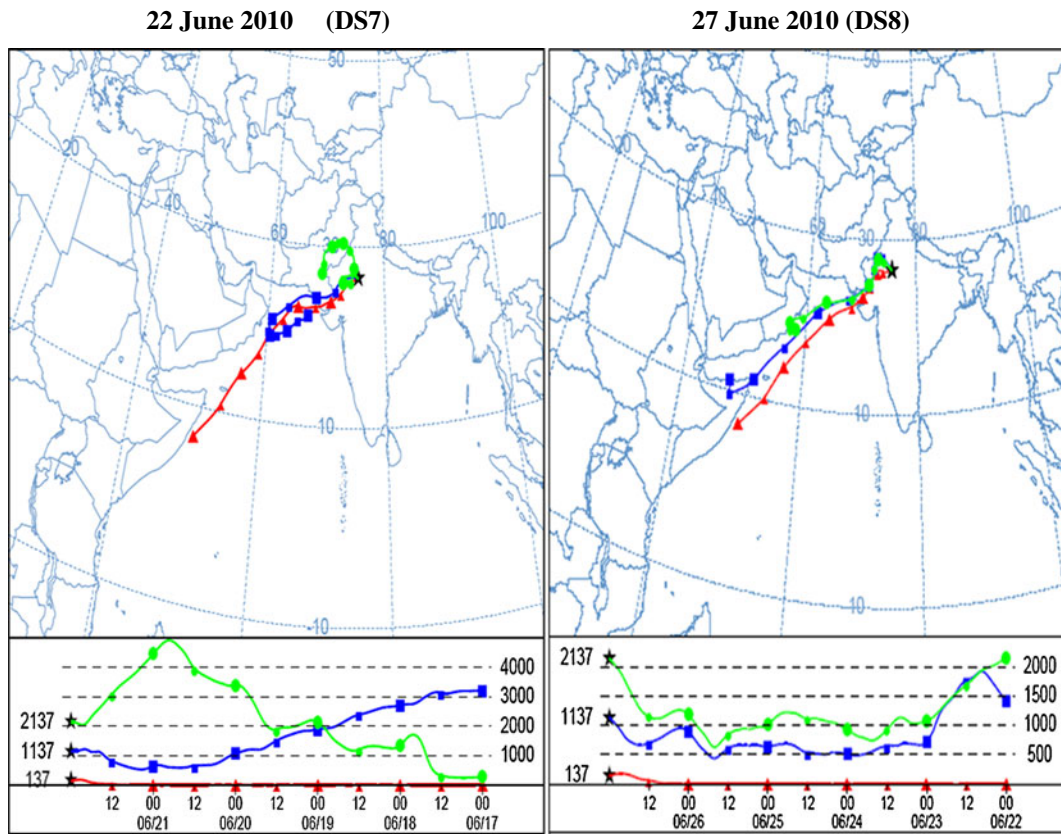


Fig. 8 (continued)

**Transport pathways of dust storms**

Figure 8 illustrates the transport pathway and origin of dust particles with 120-h back trajectories calculated for three different heights (500, 1,500, and 2,500 m AMSL) at 00 UTC over Jaipur by using the NOAA HYSPLIT trajectory model. Here, we show the air mass trajectory simulations in detail for the noted dust outbreaks recorded over Jaipur during the pre-monsoon seasons of 2009 and 2010. For all dust storms in the pre-monsoon season of 2009–2010, three groups of air masses were identified to pass over Jaipur, as shown in Fig. 8. Air mass back trajectories during dust events in May–June 2009 and 2010 suggest that the sources of loading from the Thar Desert and also long-range transport from far western arid regions of the Arabian Peninsula and Oman. Dust storms in the IGP during the pre-monsoon season have been associated with dusts lifted mainly from the Thar Desert and arid regions farther west along the path of the westerlies (Gautam et al. 2007). The air mass trajectories clearly identify

Thar Desert as the main source of the dusts except in case of the DS5, where the air mass at higher altitude seems to originate from the gulf region. The buildup of the temperature gradient at lower levels due to the development of a heat low over the arid regions of northwest India during May pulls low-level westerly flow from the Arabian sea and the Somali low-level jet (Shrestha et al. 2010). A synoptic air mass flowing southwesterly during pre-monsoon season results in frequent dust loading. The transport pathway from the westerly direction could be thus identified as dust dominant pathway due to the presence of Thar Desert. The air masses trajectories (Fig. 8) further confirm that dust-dominated westerly–southwesterly winds have a strong impact on the AOT spectrum.

**Conclusions**

The present study reports on the ambient aerosol optical characteristics over an urban site at Jaipur in the

vicinity of the dust-source region in northwestern India during 2009–2010. The paper documents the characteristics of aerosol optical properties including aerosol optical depth, volume size distribution, spectral SSA as observed from a CIMEL sun photometer instrument part of AERONET.

Our observations indicate that Jaipur is strongly influenced by enhanced dust storm activity in May–June. A series of dust storms were identified and changes in aerosol optical properties were analyzed as part of study over Jaipur in pre-monsoon season during 2009–2010.

The seasonal variations of aerosol characterization indicate progressive buildup of AOT in April which peaks in May–June followed by a decline in July, August and September consistent with the peak monsoon months over northern India. Significantly high dust storms were observed over Jaipur as indicated by high values of AOT  $0.575 \pm 0.18$  (May–June<sub>mean</sub>) and SSA ( $SSA_{440\text{ nm}}=0.89$ ,  $SSA_{675\text{ nm}}=0.95$ ,  $SSA_{870\text{ nm}}=0.97$ ,  $SSA_{1,020\text{ nm}}=0.976$ ) during pre-monsoon season than the previously reported values over IGP region sites. The dust storms also lead to a high increase in the volume concentration at the coarse mode in pre-monsoon season. The Ångström exponent was found to be inversely related to the AOT in pre-monsoon season, indicating a relatively high ratio of large particles to small particles due to dust loading in this season. Our results confirm that, the region is characterized by dust dominated source of aerosols which is relatively scattering in nature compared to background anthropogenic aerosol loading.

During the course of this study, the mean and standard deviation of SSA and AP over Jaipur were estimated as  $0.95 \pm 0.018$  and  $0.712 \pm 0.017$  at 675 nm wavelength, respectively. The comparisons of AP and Ångström exponent over Jaipur region is done to other dust-impacted areas of Kanpur and Gandhi college AERONET sites in the IGP region reveals a marked decrease in AE values and further confirms that this site is greatly affected by dust source. In general, dust is more scattered and less absorbing than that observed in the Kanpur and Gandhi college AERONET sites in IGP regions.

Despite its vicinity to urban infrastructure and thus exposure to vehicular emission sources, the site yield a clear and significant signal of elevated AOT owing to transported dust during the pre-monsoon season. The dust-dominated southwesterly winds indicate a strong

impact on the AOT spectrum. The air mass trajectories indicate Thar Desert as the main source of the dust to the region as well as significant long-range transport from the Arabian Peninsula and Oman gulf regions.

Information on aerosol optical properties near desert regions is of great importance to ascertain the aerosol scattering/absorbing nature, especially due to the lack of measurements over northwestern India. The present results are thus important and would offer the basic data for evaluating the effects of dust pollution on the regional climate, health, ecological risk assessment and management.

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## References

- Andrews, E., Sheridan, P. J., Fiebig, M., McComiskey, M., Ogren, J. A., Arnott, P., et al. (2006). Comparison of methods for deriving aerosol asymmetry parameter. *Journal of Geophysical Research*, *111*, D05S04.
- Ångström, A. (1964). The parameters of atmospheric turbidity. *Tellus*, *16*, 64–75.
- Beegum, S. N., Moorthy, K. K., Nair, V. S., Babu, S. S., Satheesh, S. K., Vinoj, V., et al. (2008). Characteristics of spectral aerosol optical depths over India during ICARB. *Journal of Earth System Science*, *117*, 303–313.
- Bonasoni, P., Laj, P., Marinoni, A., Sprenger, M., Angelini, F., Arduini, J., et al. (2010). Atmospheric brown clouds in the Himalayas: first two years of continuous observations at the Nepal Climate Observatory-Pyramid (5079 m). *Atmospheric Chemistry and Physics*, *10*, 7515–7531. doi:10.5194/acp-10-7515-2010.
- Chinnam, N., Dey, S., Tripathi, S. N., & Sharma, M. (2006). Dust events in Kanpur, Northern India: chemical evidence for source and implications to radiative forcing. *Geophysical Research Letters*, *33*, L08803. doi:10.1029/2005GL025278.
- Decesari, S., Facchini, M. C., Carbone, C., Giulianelli, L., Rinaldi, M., Finessi, E., et al. (2010). Chemical composition of PM10 and PM1 at the high-altitude Himalayan station Nepal Climate Observatory-Pyramid (NCO-P) (5079 m.a.s.l.). *Atmospheric Chemistry and Physics*, *10*, 4583–4596.

- Dey, S., & Girolamo, L. D. (2011). A decade of change in aerosol properties over the Indian subcontinent. *Geophysical Research Letters*, *38*, L14811. doi:10.1029/2011GL048153.
- Dey, S., Tripathi, S. N., Singh, R. P., & Holben, B. N. (2004). Influence of dust storms on the aerosol optical properties over the Indo-Gangetic basin. *Journal of Geophysical Research*, *109*, D20211. doi:10.1029/2004JD004924.
- Dubovik, O., & King, M. D. (2000). A flexible inversion algorithm for retrieval of aerosol optical properties from Sun and sky radiance measurements. *Journal of Geophysical Research*, *105*, 20673–20696.
- Dubovik, O., Sinyuk, A., Lapyonok, T., Holben, B. N., Mishchenko, M., Yang, P., et al. (2006). Application of spheroidal models to account for aerosol particle non-sphericity in remote sensing of desert dust. *Journal of Geophysical Research*, *111*, D11208. doi:10.1029/2005JD006619.
- El-Askari, H., Farouk, R., Ichoku, C., & Kafatos, M. (2009). Transport of dust and anthropogenic aerosols across Alexandria. *Egypt, Annales Geophysicae*, *27*, 2869–2879.
- Ganguly, D., Ginoux, P., Ramaswamy, V., Winker, D. M., Holben, B. N., & Tripathi, S. N. (2009). Retrieving the composition and concentration of aerosols over the Indo-Gangetic basin using CALIPSO and AERONET data. *Geophysical Research Letters*, *36*, L13806. doi:10.1029/2009GL038315.
- Gautam, R., Hsu, N. C., Kafatos, M., & Tsay, S. C. (2007). Influences of winter haze on fog/low cloud over the Indo-Gangetic plains. *Journal of Geophysical Research*, *112*, D05207. doi:10.1029/2005JD007036,2007.
- Gautam, R., Liu, Z., Singh, R. P., & Hsu, N. C. (2009). Two contrasting dust dominant periods over India observed from MODIS and CALIPSO data. *Geophysical Research Letters*, *36*, L06813. doi:10.1029/2008GL036967,2009.
- Gautam, R., Hsu, N. C., & Lau, K. M. (2010). Pre-monsoon aerosol characterization and radiative effects over the Indo-Gangetic Plains: implications for regional climate warming. *Journal of Geophysical Research*, *115*, D17208. doi:10.1029/2010JD013819,2010.
- Gautam, R., Hsu, N. C., Tsay, S. C., Lau, K. M., Holben, B., Bell, S., et al. (2011). Accumulation of aerosols over the Indo-Gangetic plains and southern slopes of the Himalayas: distribution, properties and radiative effects during the 2009 pre-monsoon season. *Atmospheric Chemistry and Physics*, *11*, 12841–12863. doi:10.5194/acp-11-12841-2011.
- Gobbi, G. P., Angelini, F., Bonasoni, P., Verza, G. P., Marinoni, A., & Barnaba, F. (2010). Sunphotometry of the 2006–2007 aerosol optical/radiative properties at the Himalayan Nepal Climate Observatory-Pyramid (5079 m.a.s.l.). *Atmospheric Chemistry and Physics*, *10*, 11209–11221. doi:10.5194/acp-10-11209-2010.
- Holben, B. N., Eck, T. F., Slutsker, I., Tanre, D., Buis, J. P., Setzer, A., et al. (1998). AERONET – a federated instrument network and data archive for aerosol characterization. *Remote Sensing of Environment*, *66*, 1–16.
- Huang, Y., Chameides, W. L., & Dickinson, R. E. (2007). Direct and indirect effects of anthropogenic aerosols on regional precipitation over East Asia. *Journal of Geophysical Research*, *112*, D03212. doi:10.1029/2006JD007114.
- Kahn, R. A., Nelson, D. L., Garay, M., Levy, R. C., Bull, M. A., Martonchik, J. V., et al. (2009). MISR aerosol product attributes and statistical comparison with MODIS. *IEEE Transactions on Geoscience and Remote Sensing*, *47*(12), 4095–4114.
- Kaskaoutis, D. G., Kalapureddy, M. C. R., Krishna Moorthy, K., Devara, P. C. S., Nastos, P. T., Kosmopoulos, P. G., et al. (2010). Heterogeneity in pre-monsoon aerosol types over the Arabian Sea deduced from ship-borne measurements of spectral AOTs. *Atmospheric Chemistry and Physics*, *10*, 4893–4908. doi:10.5194/acp-10-4893-2010.
- Kaufman, Y. J., & Fraser, R. S. (1997). The effect of smoke particles on cloud and climate forcing. *Science*, *277*, 1636–1639.
- Kotchenruther, R., Hobbs, P. V., & Hegg, D. A. (1999). Humidification factors for atmospheric aerosols off the mid-Atlantic coast of the United States. *Journal of Geophysical Research*, *104*, 2239–2251.
- Lau, K.-M., & Kim, K.-M. (2006). Observational relationships between aerosol and Asian monsoon rainfall, and circulation. *Geophysical Research Letters*, *33*, L21810. doi:10.1029/2006GL027546.
- Lau, K.-M., Kim, M. K., & Kim, K. M. (2006). Asian monsoon anomalies induced by aerosol direct effects. *Climate Dynamics*, *26*, 855–864. doi:10.1007/s00382-006-0114.
- Lawrence, M. G., & Lelieveld, J. (2010). Atmospheric pollutant outflow from southern Asia: a review. *Atmospheric Chemistry and Physics*, *10*, 11017–11096.
- Léon, J.-F., & Legrand, M. (2003). Mineral dust sources in the surroundings of the north Indian Ocean. *Geophysical Research Letters*, *30*(6), 1309. doi:10.1029/2002GL016690.
- Meehl, G. A., Arblaster, J. M., & Collins, W. D. (2008). Effects of black carbon aerosols on the Indian monsoon. *Journal of Climate*, *21*, 2869–2882.
- Moorthy, K. K., Babu, S. S., Satheesh, S. K., Srinivasan, J., & Dutt, C. B. S. (2007). Dust absorption over the "Great Indian Desert" inferred using ground-based and satellite remote sensing. *Journal of Geophysical Research*, *112*, D09206. doi:10.1029/2006JD007690.
- Nair, V. S., Moorthy, K. K., Alappattu, D. P., Kunhikrishnan, P. K., George, S., Nair, P. R., et al. (2007). Wintertime Aerosol Characteristics over the Indo-Gangetic Plain (IGP): impacts of local boundary layer processes and long range transport. *Journal of Geophysical Research*, *112*, D13205.
- Pandithurai, G., Dipu, S., Dani, K. K., Tiwari, S., Bisht, D. S., Devara, P. C. S., et al. (2008). Aerosol radiative forcing during dust events over New Delhi, India. *Journal of Geophysical Research*, *113*, D13209. doi:10.1029/2008JD009804.
- Pant, P., Hegde, P., Dumka, U. C., Sagar, R., Satheesh, S. K., Moorthy, K. K., et al. (2006). Aerosol characteristics at a high-altitude location in central Himalayas: optical properties and radiative forcing. *Journal of Geophysical Research*, *111*, D17206. doi:10.1029/2005JD006768.
- Parameswaran, K., & Vijayakumar, G. (1994). Effect of relative humidity on aerosol size distribution. *Indian Journal of Radio and Space Physics*, *23*(3), 175–188.
- Pease, P. P., Tchakerian, V. P., & Tindale, N. W. (1998). Aerosols over the Arabian Sea: geochemistry and source areas for aeolian desert dust. *Journal of Arid Environments*, *39*, 477–496.
- Prasad, A. K., & Singh, R. P. (2007). Changes in aerosol parameters during major dust storm events (2001–2005)

- over the Indo-Gangetic Plains using AERONET and MODIS data. *Journal of Geophysical Research*, *112*, D09208. doi:10.1029/2006JD007778.
- Prospero, J. M., Ginoux, P., Torres, O., Nicholson, S. E., & Gill, T. E. (2002). Environmental characterization of global sources of atmospheric soil dust identified with the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product. *Reviews of Geophysics*, *40*(1), 1002. doi:10.1029/2000RG000095.
- Ram, K., Sarin, M. M., & Hegde, P. (2010). Long-term record of aerosol optical properties and chemical composition from a high-altitude site (Manora Peak) in Central Himalaya. *Atmospheric Chemistry and Physics*, *10*, 11791–11803. doi:10.5194/acp-10-11791-2010.
- Ramanathan, V., Crutzen, P. J., Kiehl, J. T., & Rosenfeld, D. (2001). Aerosols, climate, and the hydrological cycle. *Science*, *294*, 2119. doi:10.1126/science.1064034.
- Ramanathan, V., Li, F., Ramana, M. V., Siva, P. S., Kim, D., Corrigan, C. E., et al. (2007). Atmospheric brown clouds: hemispherical and regional variations in long range transport, absorption and radiative forcing. *Journal of Geophysical Research*, *112*. doi:10.1029/2006JD008124.
- Russell, P. B., Bergstrom, R. W., Shinzuka, Y., Clarke, A. D., DeCarlo, P. F., Jimenez, J. L., et al. (2010). Absorption Ångström exponent in AERONET and related data as an indicator of aerosol composition. *Atmospheric Chemistry and Physics*, *10*, 1155–1169. doi:10.5194/acp-10-1155-2010.
- Sabbah, I., Ichoku, C., Kaufman, Y. J., & Remer, L. A. (2001). Full year cycle of desert dust spectral optical thickness and precipitable water vapor over Alexandria, Egypt. *Journal of Geophysical Research*, *106*, 18305–18316.
- Satheesh, S. K., Moorthy, K. K., Kaufman, Y. J., & Takemura, T. (2006). Aerosol optical depth, physical properties and the radiative forcing over the Arabian Sea. *Meteorology and Atmospheric Physics*, *91*, 45–62.
- Shrestha, P., Barros, A. P., & Khlystov, A. (2010). Chemical composition and aerosol size distribution of the middle mountain range in the Nepal Himalayas during the 2009 pre-monsoon season. *Atmospheric Chemistry and Physics*, *10*, 11605–11621. doi:10.5194/acp-10-11605-2010.
- Sikka, D. R. (1997). Desert climate and its dynamics. *Current Science*, *72*(1), 35–46.
- Singh, R. P., Dey, S., Tripathi, S. N., Tare, V., & Holben, B. (2004). Variability of aerosol parameters over Kanpur, northern India. *Journal of Geophysical Research*, *109*, D23206. doi:10.1029/2004JD004966.
- Smirnov, A., Holben, B. N., Eck, T. F., Slutsker, I., Chatenet, B., & Pinker, R. T. (2002). Diurnal variability of aerosol optical depth observed at AERONET (Aerosol Robotic Network) sites. *Journal of Geophysical Research Letters*, *29*(23), 2115. doi:10.1029/2002GL016305.
- Soni, K., Singh, S., Bano, T., Tanwar, R. S., Nath, S., & Arya, B. C. (2010). Variations in single scattering albedo and Ångström absorption exponent during different seasons at Delhi, India. *Atmospheric Environment*, *44*, 4355–4363. doi:10.1016/j.atmosenv.2010.07.058.
- Srivastava, A. K., Tiwari, A. K., Devara, P. C. S., Bisht, D. S., Srivastava, M. K., Tripathi, S. N., et al. (2011). Pre-monsoon aerosol characteristics over the Indo-Gangetic Basin: implications to climatic impact. *Annals of Geophysics*, *29*, 789–804.
- Tanre, D., Haywood, J., Pelon, J., Leon, J. F., Chatenet, B., Formenti, P., et al. (2003). Measurement and modeling of the Saharan dust radiative impact: overview of the Saharan Dust Experiment (SHADE). *Journal of Geophysical Research*, *108*, 8574. doi:10.1029/2002JD003273.
- Verma, S., Worden, J., Payra, S., Jourdain, L., & Shim, C. (2008). Characterizing the long-range Transport of Black Carbon Aerosols during Transport and Chemical Evolution over the Pacific (TRACE-P) Experiment. *Environmental Monitoring and Assessment*, *154*(1–4), 85–92. doi:10.1007/s10661-008-0379-2. Springer.
- Wang, C., Kim, D., Ekman, A. M. L., Barth, M. C., & Rasch, P. J. (2009). Impact of anthropogenic aerosols on Indian summer monsoon. *Geophysical Research Letters*, *36*, L21704. doi:10.1029/2009GL040114.
- Washington, R., Todd, M., Middleton, N. J., & Goudie, A. S. (2003). Dust storm source areas determined by the Total Ozone Monitoring Spectrometer and surface observations. *Annals of the Association of American Geographers*, *93*, 297–313.