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Influence of anomalous dry conditions on aerosols over India: Transport, distribution and properties

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Influence of anomalous dry conditions on aerosols over India: Transport, distribution and properties

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[1] A synergy of satellite and ground-based radiometric observations, along with chemical transport modeling, was used for the assessment of the influence of drought monsoon conditions of 2002 and prolonged dry pre-monsoon period of 2003 on aerosol properties over south Asia, with emphasis over northern India. Reanalysis data are also examined for studying the dry anomalous period from the climatological mean, that show prevalence of westerlies under anticyclonic circulation and subsidence favoring the accumulation of aerosols. TRMM observations over south Asia indicate significant rainfall deficit over northwestern India in July 2002 and May–June 2003. Subsequently, the anomalous and prolonged dry conditions favored heavy aerosol buildup as indicated by strong positive anomalies (20–80%) of MODIS aerosol optical depth (AOD) as well as significant increase in TOMS aerosol index (AI) during July 2002 and May–June 2003 compared to the long-term monthly means. The largest increase in aerosol loading is observed over northern India, encompassing the Indo-Gangetic Plains (IGP) that is in the downwind region of dust outflow from the Thar Desert and long-range transport from Arabia and Middle East. Ground-based sunphotometer observations at Delhi and Kanpur also show enhanced presence of desert-dust aerosols during July 2002 and May–June 2003, characterized by large AOD and significantly low Angstrom Exponent. In addition, modifications in columnar aerosol size distribution toward larger coarse-mode fraction and higher single scattering albedo at longer wavelengths were observed, thus supporting the observation of enhanced dust influx. SPRINTARS model simulations also show the enhanced dust loading over northern India during the studied months, which is in general agreement with the satellite and ground-based observations.

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1. Introduction

[2] The aerosol properties over Indian sub-continent exhibit large seasonal and inter-annual variations mainly driven by the regional monsoon system, the associated changes in source types and their distributions and seasonally changing air masses [*Singh et al.*, 2004; *Jethva et al.*, 2005; *Gautam et al.*, 2007; *Gogoi et al.*, *2009*; *Kaskaoutis et al.*, 2009; *Henriksson et al.*, 2011]. In general, there is a well-defined increasing trend in total and anthropogenic aerosols observed over the northern parts of India [*Sarkar et al.*, 2006; *Prasad and Singh*, 2007a; *Kaskaoutis et al.*, 2011a; *Dey and Di Girolamo*, 2011]; however, the inter-annual variations and trends of naturally produced aerosols (e.g., mineral dust) remain largely uncertain and are strongly dependent on regional rainfall and wind patterns, movement of the Inter-Tropical Convergence Zone (ITCZ), Quasi-Biennial Oscillation (QBO) and El-Nino – La Nina phases [*Krishnamurti et al.*, 1998; *Gautam et al.*, 2009a; *Bhawar and Devara*, 2010; *Abish and Mohanakumar*, 2012].

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[3] During pre-monsoon season (April–June), the synoptic weather patterns are characterized by dominant westerly winds that cause influx of dust aerosols over northern India from the Thar desert, Middle East and Arabian Peninsula regions [*Prospero et al.*, 2002; *Dey et al.*, 2004; *Lawrence and Lelieveld*, 2010]. The dust mixed with anthropogenic emissions forms a thick absorbing aerosol layer extending up to 5 km, constituting bulk of the regional aerosol loading, and has been postulated to have amplified the observed mid-tropospheric warming over the elevated Hindu-Kush – Himalayan ranges [*Gautam et al.*, 2009b, 2010]. Since the pre-monsoon meteorological and atmospheric conditions are critical for the onset, intensity and duration of the monsoon, several studies have focused on examining the aerosol and climate implications during this period [e.g., *Singh et al.*, 2005, 2010; *El-Askary et al.*, 2006; *Lau et al.*, 2006; *Lau and Kim*, 2006; *Gautam et al.*, 2009c, 2011; *Das and Jayaraman*, 2011; *Giles et al.*, 2011]. On the other hand, the active and break spells of the monsoon have also been shown to have significant influence on the accumulation of aerosols and associated climate implications [*Bhuiyan et al.*, 2009a, 2009b; *Ravi Kiran et al.*, 2009; *Manoj et al.*, 2011].

[4] Due to increased scientific interest in the aerosol-climate interactions, several climate modeling-based studies have dealt with aerosol-monsoon linkage over south Asia and different scenarios have been proposed. On the one hand, *Ramanathan et al.* [2005] suggested that the Indian summer monsoon rainfall may weaken as a result of aerosol-induced surface dimming, due to sea surface cooling and reduced evaporation over the Indian Ocean, which suppress precipitation during the southwest monsoon season. In contrast, other scenarios [*Lau et al.*, 2006; *Lau and Kim*, 2006] suggest that the solar absorption by higher soot and dust concentrations over northern India may strengthen the meridional overturning and, in turn, increase early summer monsoon (May–June) rainfall through the elevated heat pump mechanism. Additionally, via simulations of BC aerosols in a global climate model, *Meehl et al.* [2008] found an increase in pre-monsoon (March–June) and a decrease in monsoon (July–August) rainfall due to absorbing aerosols. *Collier and Zhang* [2009] arrived at similar findings of a pre-monsoon increase and a monsoon decrease of precipitation due to aerosol solar absorption using NCAR-CAM 3 model simulations. Additionally, higher aerosol loading and associated impacts on land-atmosphere interactions may perturb mesoscale monsoon rainfall characteristics over northern India [*Niyogi et al.*, 2007]. Therefore, the radiative impacts of aerosols related to strengthening or weakening of the monsoon over south Asia are two complicated phenomena that remain largely unknown and, thus, require the better understanding of inter-annual variations of regional meteorology and accumulation of aerosol loading and optical/radiative properties.

[5] The present study examines the anomalous meteorological conditions and associated effects on aerosol loading distribution and properties during periods of anomalous dry conditions in monsoon and late pre-monsoon seasons of 2002 and 2003 over India, respectively, mainly focusing over the Indo-Gangetic Plains (IGP). In this respect, the anomaly from the climatological mean is examined for pressure systems, rainfall, Aerosol Optical Depth (AOD), Aerosol Index (AI) and aerosol optical properties over India in general, and Delhi and Kanpur in the IGP in particular, by means of NCEP/NCAR re-analysis data, satellite (TRMM, MODIS, TOMS) observations, ground-based measurements and chemical model (SPRINTARS) simulations. Although previous studies [*Gadgil et al.*, 2003; *Sikka*, 2003] have examined the drought monsoon conditions in July 2002, mainly from the meteorological and hydrological aspect, the present study examines the effects of the drought/prolonged dry conditions of monsoon 2002 and pre-monsoon 2003 on aerosol characteristics over northern India.

2. Data Set and Methodology

2.1. Atmospheric Circulation Data (NCEP/NCAR)

[6] The atmospheric circulation data is obtained from the National Center Environmental Prediction/National Center Atmospheric Research (NCEP/NCAR) Reanalysis Project [*Kalnay et al.*, 1996]. It consists of monthly values of mean sea level pressure (MSLP) and 700 hPa geopotential height (Z700) for the period 1998–2009, at 2.5° × 2.5° spatial resolution, covering a broad region of South Asia, from 45° to 100°E and from 5° to 50°N. The 700 hPa level has been selected since at this altitude (∼3000 m) dust transport is more intense and frequent [*Gkikas et al.*, 2012].

2.2. TRMM Rainfall Data

[7] The monthly normalized (%) rainfall anomaly over south Asia during the period April–July for 2002 and 2003 was obtained via Giovanni online visualization system from Tropical Rainfall Measuring Mission (TRMM) rainfall climatology (3B43 V6) for the period 1998–2009. More details about TRMM 3B43 V6 can be found in *Huffman et al.* [2007]. The spatial resolution of the gridded data set is at 0.25° × 0.25° covering the area 0–35°N, 60–95°E and the % anomaly in rainfall is discussed in view of meteorological patterns and atmospheric aerosols. In order to analyze the rainfall variation over arid regions in northwestern India and Pakistan (22–30°N, 65–79°E) the TRMM data were also analyzed during May–July 1998–2009.

2.3. MODIS Data

[8] The Terra-MODIS AOD_{550} (at 550 nm) for the months April–July was obtained over Indian sub-continent (0–30°N, 60–95°E) covering the period 2000–2009, in Level-3 gridded form with 1° × 1° spatial resolution. The AOD_{550} corresponds to collection 5, following the dark-target approach for aerosol retrievals over land with lack of data over the deserts [*Levy et al.*, 2007]. Since there is lack of data over bright surfaces and cloudy conditions, therefore to minimize sampling bias, the spatial distribution of the AOD anomalies is shown for each month when a sufficient number of MODIS retrievals (above 10 days) occur over a specific pixel; otherwise the AOD anomaly remains undetermined (white gaps in Figure 4). In addition to the dark target aerosol retrievals, AOD_{550} values from Terra-MODIS Deep Blue algorithm [*Hsu et al.*, 2004], that includes retrievals over bright arid regions, were obtained over Thar desert (25°–30°N, 69°–78°E) to analyze the spatiotemporal variations of AOD over the source region.

2.4. TOMS Data

[9] In addition to MODIS, long-term (1979–2005) data set of AI for the months April–July were obtained over south Asia (8–35°N, 45–95°E) from the Total Ozone Mapping Spectrometer (TOMS) onboard Nimbus-7 (1979–1992) and Earth Probe (1997–2005) satellites [*Hsu et al.*, 1996; *Herman et al.*, 1997; *Torres et al.*, 1998], since TOMS is highly successful in detecting absorbing aerosols over bright desert areas [*Hsu et al.*, 1999]. The AI values correspond to version 8 at a spatial resolution of 1° × 1.25° and are monthly averaged.

2.5. Ground-Based Column Aerosol Measurements

[10] Spectral AOD and Ångström exponent (α) daily values have been taken from Kanpur AERONET station (26.5°N, 80.2°E) operating since 2001 [*Singh et al.*, 2004]. Systematic direct-beam and sun/sky almucantar radiance measurements have been performed using Cimel (CE-318) sun/sky radiometer, which provides the spectral AODs at eight wavelengths, from 340 to 1640 nm, and the water vapor content at 940 nm using its internal calibration for direct-beam irradiance recordings [*Holben et al.*, 1998]. Furthermore, via the almucantar measurements and the Spectral Deconvolution Algorithm (SDA), retrievals of aerosol columnar size distribution (CSD), single scattering albedo (SSA), asymmetry parameter, refractive index, fine and coarse-mode AODs are also available for large zenith angles (>50°) and higher aerosol loading (AOD_{440} > 0.4) conditions [*Dubovik et al.*, 2000]. The Level 2 (cloud screened and quality assured) AERONET data were used in the present study following the uncertainties in the retrievals described elsewhere [*Smirnov et al.*, 2000; *Dubovik et al.*, 2002]. More specifically, the values of AOD_{500} and $\alpha_{440-870}$ from AERONET retrievals were used as well as those of $\alpha_{380-500}$ and $\alpha_{675-870}$ obtained via Volz method. The error in spectral AOD as given by AERONET is below ~0.02, while the respective errors in α is below ~5% since, due to large AOD values over Kanpur throughout the year, the errors in parameters related with aerosol size are limited. Furthermore, the CSD and the spectral SSA were used as monthly averaged values for the months April–July during 2002, 2003 and for the whole period (2001–2010).

[11] In addition, spectral AODs over Delhi (28°N, 77°E) located about 400 km northwest of Kanpur have been used for the period April–July, 2002–2010. The spectral AODs were obtained via Microtops-II (MT) Sun photometer and ozonometer instruments [*Soni et al.*, 2011] in the campus of the National Physical Laboratory (NPL). In order to avoid any discrepancy in the actual sun-disk targeting, since MT is a manually operated instrument, it is placed on a tripod stand. Furthermore, in order to attain as high accuracy as possible in the spectral AOD retrievals, two MT units were operated simultaneously. One takes measurements at 340, 500, 675, 870 and 1020 nm, while the other at 340, 500, 870, 936, and 1020 nm. Both instruments are calibrated once per year alternately. The data used in the present study are the spectral AODs at the 4 common wavelengths i.e., 340, 500, 870 and 1020 nm and the Ångström exponent values obtained using least squares method in the wavelength range 340–1020 nm. The comparison between the two MT measurements at 500 nm show a general agreement of 0.03 in absolute AOD values, which is within the uncertainty (±0.03) of MT measurements [*Morys et al.*, 2001]. The spectral AODs were further filtered for removing possible cloud contamination by applying the methodology suggested by *Kaskaoutis et al.* [2011b], i.e., by examining the consistency of $\alpha_2 - \alpha_1 = \alpha$ relationship (α_2 and α_1 are the constant terms of the second order polynomial fit in the lnAOD versus lnλ); after removing some large scattered values, the entire set of MT measurements during the months April–July was analyzed for the period 2002–2010.

2.6. SPRINTARS Simulations

[12] A global three-dimensional aerosol transport-radiation model, the Spectral Radiation-Transport Model for Aerosol Species (SPRINTARS) was also used to simulate aerosols over south Asia. SPRINTARS is implemented in both an atmospheric general circulation model (AGCM) developed by the Center for Climate System Research of the University of Tokyo, National Institute for Environmental Studies and the Frontier Research Center for Global Change [*K-1 Model Developers*, 2004] (hereafter referred to as MIROC AGCM), and a radiation transfer with a k-distribution scheme, MSTRN-8 [*Nakajima et al.*, 2000]. The model is able to simulate AOD for each component; i.e., soil dust, sea salt, BC, organic carbon, sulfate, ammonium and nitrate. The simulations were conducted with nudged meteorological fields from the NCEP/NCAR reanalysis data (wind field, water vapor and temperature) with the T42 horizontal resolution (approximately 2.8° by 2.8° in latitude and longitude). In SPRINTARS model, emission processes for dust with 10 bins ranging from 0.13 to 8.2 μm are online-calculated according to an empirical relation by *Gillette* [1978], depending on near-surface wind speed above a threshold of 6.5 ms^{-1}, soil moisture and snow amount [*Takemura et al.*, 2000; *Goto et al.*, 2011a]. For the other components (sulfates, nitrates, organics, sea salt, etc), emission processes and inventories are described by *Goto et al.* [2011b, 2011c], which use the anthropogenic SO_2 and BC emission fluxes from *Streets et al.* [2003] over Asia. Transitions of the emission strength for anthropogenic matters were based on emission inventories widely used in the AeroCom project. SPRINTARS model was recently used to simulate aerosol emission and properties over Hyderabad, India [*Goto et al.*, 2011b] and selected AERONET sites over south and east Asia [*Goto et al.*, 2011d] with promising results. In the present study, the model is applied for the simulation of the total AOD, dust AOD and dust contribution over south Asia (0–40°N, 40–100°E) during the period 2000–2008, mainly emphasizing on the anomaly in dust AOD during April–July months of 2002 and 2003.

3. Results and Discussion

[13] As we outlined earlier in section 1, our objective is to highlight the anomalous prolonged dry conditions during the monsoon and late pre-monsoon periods of 2002 and 2003, respectively, and draw their association with enhanced aerosol loading over northern India. We identified the 2002 monsoon period, specifically July, and 2003 late pre-monsoon period, specifically late May – early June, when anomalous prolonged dry conditions prevailed over northern India associated with significantly lower rainfall. In the following

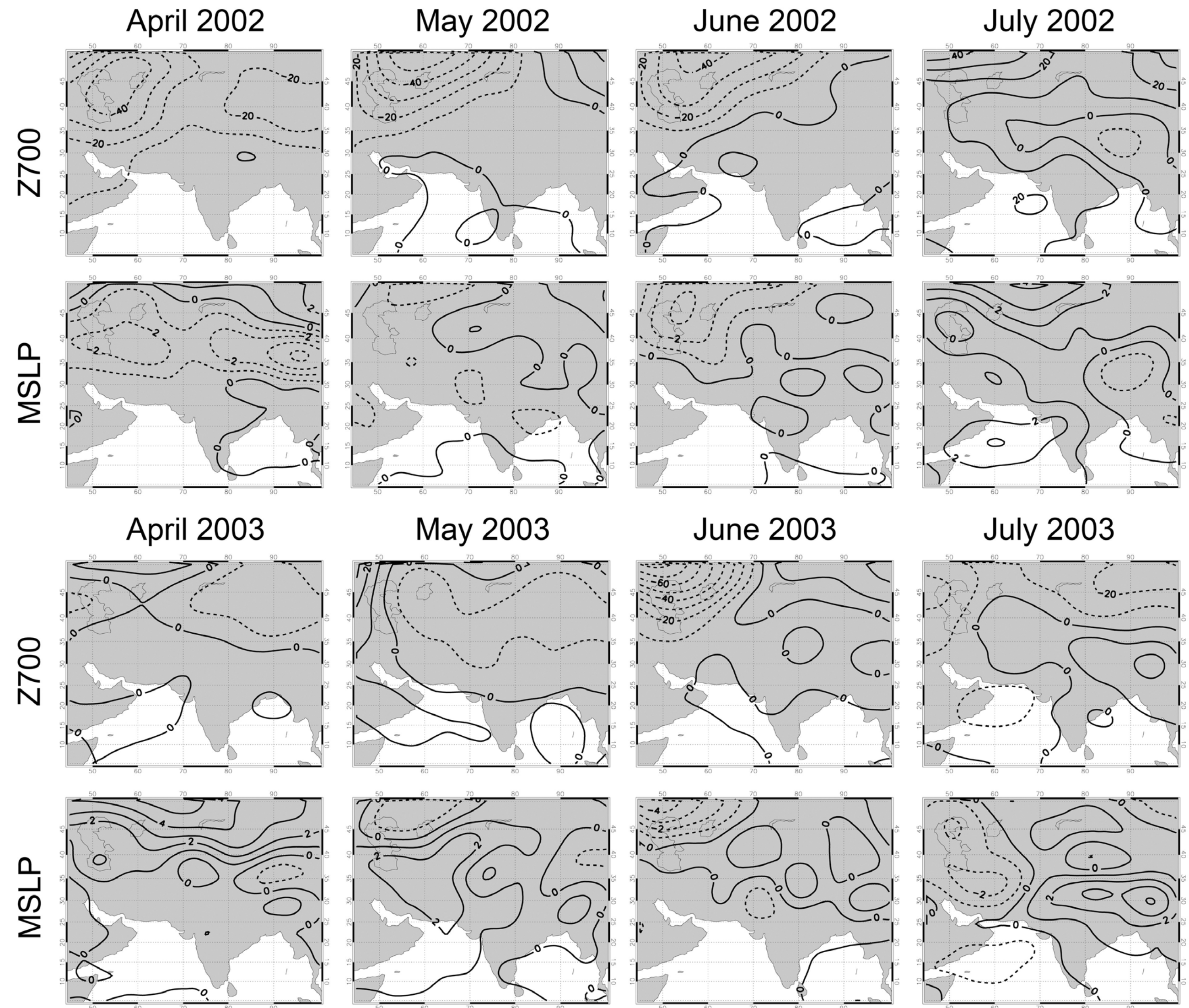

Figure 1. Mean sea level pressure (MSLP) and 700 hPa geopotential height (Z700) anomaly patterns (in hPa and gpm respectively) from the average of the period 1998–2009, for (top two rows) April–July 2002 and (bottom two rows) April–July 2003.

sections, the general atmospheric and meteorological regime during 2002 and 2003 is reviewed highlighting the below normal rainfall that favored persistence of dry conditions and accumulation of aerosols over northern India. The enhanced aerosol loading is assessed by a synergistic approach using a combination of satellite and ground-based column integrated observations of aerosols and optical properties. The aerosol characterization is followed by analysis of chemical transport model simulations focusing on transported dust, thus providing support to the general theme of the paper i.e., anomalous dry conditions leading to enhanced aerosol loading over the Indian monsoon region.

3.1. Atmospheric Circulation and Precipitation Regime in 2002 and 2003

[14] The anomaly patterns of the MSLP and Z700 fields for the months April–July 2002 and 2003, from the climatological mean of the period 1998–2009, are shown in Figure 1. This section is focused on the two anomalous dry periods as noted previously. First, during July 2002, when India experienced a major drought, positive pressure and geopotential height anomalies influence the Arabian Sea (AS) and most of the Indian subcontinent, while negative anomalies cover the eastern part of the Bay of Bengal (BoB). Near the surface, the highest values (above 2 hPa) are found over the AS while at 700 hPa level more than 20 gpm are seen over the Khambhat Gulf. The positive anomalies in MSLP imply the weakening of the usually prevailing cyclonic circulation in this region, and consequently, the weakened southwest flow of humid air over India, the main feature of the monsoon period. A detailed examination of the daily synoptic conditions (figures not shown) indicated that the southwest Asia summer low of oblong shape appears split in two weak centers, one over southern Arabia and another over northern India. The latter, combined with the relatively high pressures over the AS, induced stronger and/or more frequent dry northwesterly winds of continental origin over western India causing drier weather conditions.

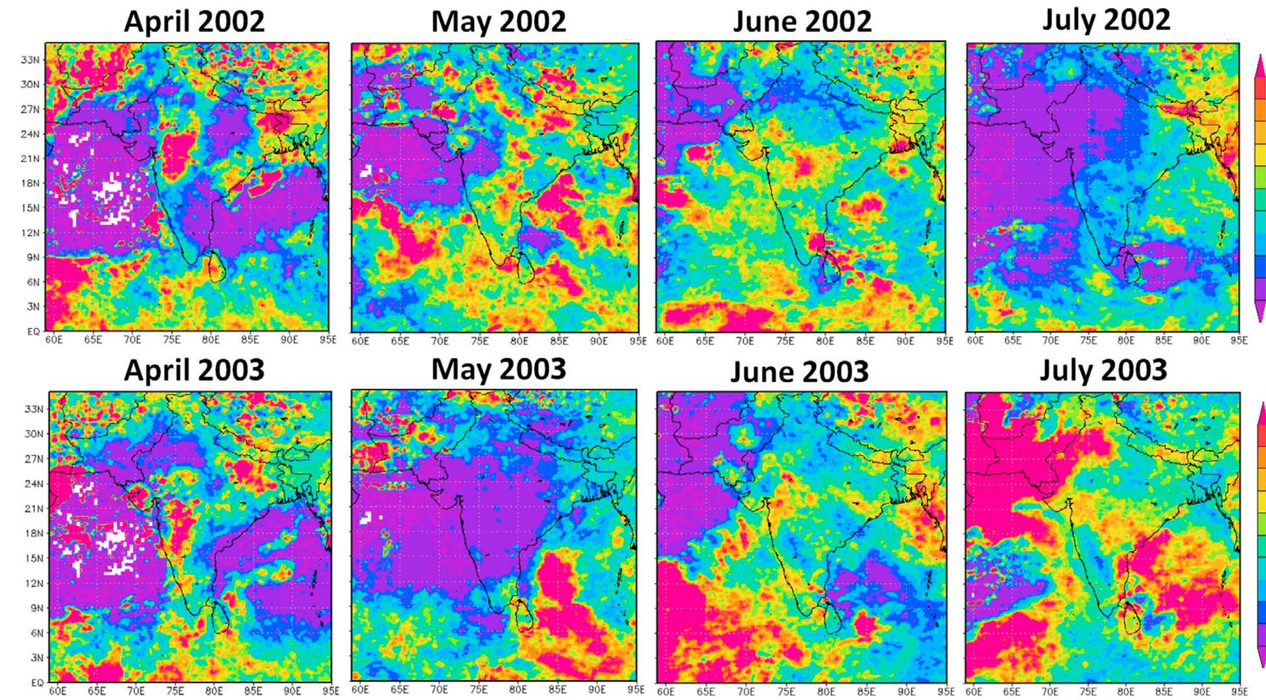

Figure 2. Monthly normalized rainfall anomaly (%) for April, May, June and July of 2002 and 2003 based on the monthly rainfall climatology of TRMM 3B43 V6 during the period 1998–2009.

Also, at 700 hPa height, the extension of the positive anomalies up to northern and eastern India indicates a considerable deviation from the usual cyclonic circulation. Indeed, most of the daily synoptic conditions (not shown) present anticyclonic circulations prevailing over the region.

[15] Furthermore, *Ghude et al.* [2011] analyzed the anomalies in horizontal wind and vertical circulation over Indian region associated the subsidence during July 2002, showing less convection of trace gases, significant reduction in moisture and less photochemical formation of tropospheric ozone over eastern India. They also found westerly wind anomalies of 10 ms^{-1} at 850 hPa over IGP, indicating anti-cyclonic vorticity that does not support convection over the area and leading to the weak monsoon in July 2002 with a negative deviation in rainfall ($\sim$10 mm/day) over the western Ghats, central India and western IGP. On the other hand, enhanced convection over tropical southeast Indian Ocean may have weakened the monsoon circulation over the Indian Ocean during July 2002 [*Sikka*, 2003].

[16] The other anomalous dry period we identified previously is during the late pre-monsoon of 2003. In May 2003, the anomaly pattern, in general, is similar to that of July 2002 but not as pronounced; namely, positive anomalies are evident over AS (above 1 hPa and 10 gpm for MSLP and Z700, respectively) and slightly negative anomalies over BoB. However, in June 2003, near the surface, northwestern India was influenced by weak negative pressure anomaly in contrast to northwestern Pakistan and Afghanistan that experienced some subsidence. As a result, the dry areas in June 2003 are confined west of the Indian peninsula (see Figure 2). At the 700 hPa level, no considerable geopotential height anomalies are found over low latitudes and in most places, normal conditions prevail. Finally, in July 2003, the negative anomalies over Iran and Afghanistan, in combination with the positive anomalies over northeastern AS and northwestern India, are associated with a strengthened southerly flow of humid air over Pakistan and northwestern India, causing enhanced rainfall in these regions (see Figure 2). It has to be mentioned that the above anomalies were also calculated from the long-term averages (60 years), as a test (figures not shown). Both MSLP and Z700 anomaly patterns were almost identical with the ones presented, confirming thus our results. Small differences were found in the values of the maxima and minima only, which were stronger for the anomalies from the 60 year averages.

[17] The TRMM normalized (%) rainfall anomaly indicates a pronounced spatial and temporal heterogeneity during April–July of 2002 and 2003 (Figure 2). The spatial distribution of the rainfall anomaly reveals a dipole-like pattern of reduced precipitation over northern AS and northwestern arid India and increase over southern AS and northern Indian Ocean. This pattern is closely associated with the dipole observed in the ongoing longwave radiation (OLR) over the region during the break and active spells of intraseasonal monsoon variability [*Manoj et al.*, 2011]. On the other hand, the north-to-south gradient in rainfall anomaly for longitudes west of $\sim$80°E (over Thar desert, source region for mineral dust) appears to be more intense during July 2002 and May–June 2003. During July 2002, most parts of India were affected by below-average rainfall causing the first all-India drought since 1987. The rainfall was below normal by $\sim$19%, on average [*Waple and Lawrimore*, 2003], and as high as negative 60–70% in Rajasthan state in northwestern India. On the other hand, the May–June period represents monsoon onset conditions over India and is typically characterized by less rain over

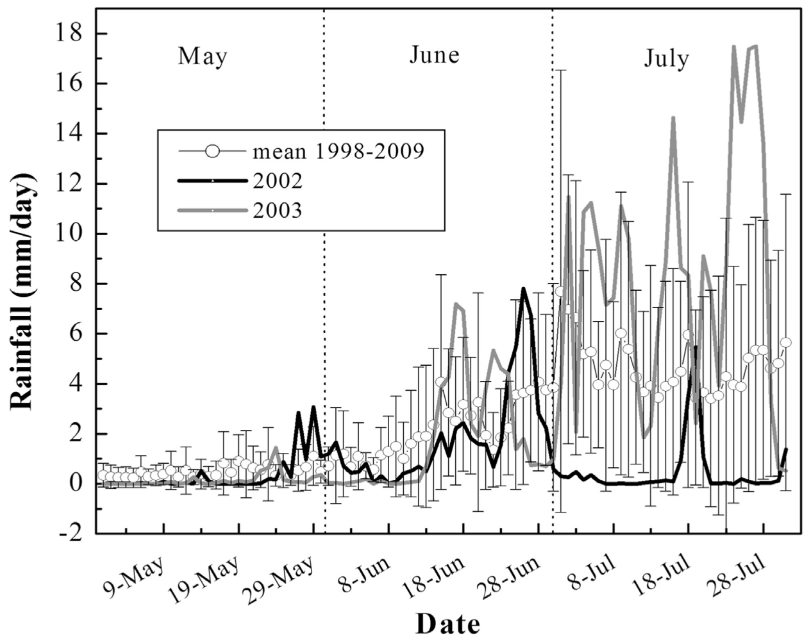

Figure 3. Daily variation of rainfall amounts obtained from TRMM during May–July for the period 1998–2009 (mean with standard deviations) and for 2002 and 2003 over northwestern India and Pakistan [22–30°N, 65–79°E].

north/northwestern India, since the monsoon usually starts toward the latter half of June and first week of July. However, May–June of 2003 was a prolonged dry period, with negligible rainfall amount (significantly lesser than the ~10-year average value) and number of rainy days over northwestern arid India. This is shown in Figure 3 where May–June 2003 is characterized by below average precipitation over the region (TRMM observations). A sustained dry period during the late pre-monsoon season during 2003, i.e., the peak dust activity period, as seen in Figure 3, may likely favor longer dust-aerosol lifetime and accumulation of aerosols over northern India, relative to a normal period when northern India experiences pre-monsoon rain showers as seen in the climatological rainfall data (Figure 3). Additionally, during first half of June 2003 several dust outbreaks occurred over northern India [*Prasad and Singh*, 2007b] that may be associated with the prolonged dry conditions as well as other factors associated with surface wind speed over the arid regions, soil moisture, convective activity, etc. The examination of these requires detailed analysis on daily basis and is beyond the scope of the present work. In general, TRMM results highlight the deficit of rainfall in July 2002 and May–June 2003 over northwestern arid India, while July 2003 was a month with above-average rainfall. During other months, pockets of increasing and decreasing rainfall are spread over the whole area with the most characteristic pattern the decrease of rainfall over northern AS and BoB and the increase over tropical Indian Ocean during April 2002 and 2003.

[18] In the following sections, the variability and anomaly in aerosol properties are examined over south Asia focusing on 2002 July and May–June 2003 over northern India. The observed anomalies are discussed in association with the meteorological and precipitation patterns.

3.2. Aerosol Field Over South Asia

[19] The percentage (%) difference in the Terra-MODIS AOD_{500} values for April–July 2002 and 2003 from the respective monthly mean decadal (2000–2009) values is shown in Figure 4. In general, the differences are positive in the vast majority of the area with more pronounced % increase over IGP (~20–80%) for the months July 2002 and May–June 2003 associated with the decrease in rainfall over the region (Figures 2 and 3). However, it should be noted that the AOD variability over a region is influenced by several parameters; in addition to rainfall amount and anomalies, i.e., number of rainy days, wind speed and direction, dust intensity, aerosol lifetime, local anthropogenic emissions, etc. Additionally, high (~40–60%) AOD increase is observed over southern parts of AS, BoB and northern Indian Ocean (NIO) during specific months; however, the AOD_{500} over these regions is quite low, therefore even a small deviation from the decadal monthly mean can lead to large % deviation. The large increase in AOD indicates accumulation of aerosols over IGP as a combination of deficit in precipitation, enhanced dust activity and atmospheric aerosol lifetime. However, the increase of AOD over IGP may be the result of both natural and anthropogenic aerosol accumulation, which is difficult to be discriminated using MODIS data due to uncertainties in fine-mode fraction over land [*Levy et al.*, 2007]. Additionally, *Ghude et al.* [2011] have shown a large subsidence during July 2002, strongly related with trapping of pollutants and increasing levels of CO near the surface over IGP. Furthermore, there is lack of data (white gaps) over the bright areas in Thar desert and Pakistan, so we cannot make a firm conclusion regarding the variation in dust activity. Therefore, the AOD retrievals from the MODIS Deep Blue algorithm [*Hsu et al.*,

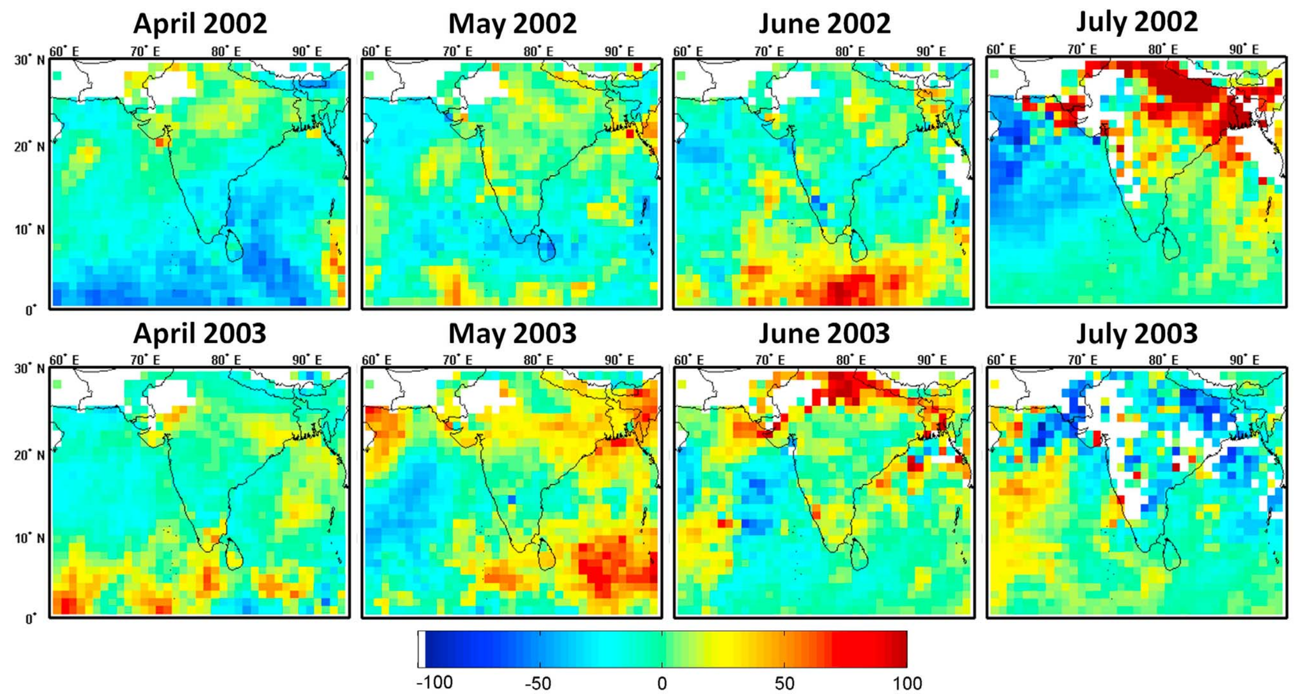

Figure 4. Percentage (%) deviation of the Terra-MODIS AOD_{550} for the months April–July of the year (top) 2002 and (bottom) 2003 from the monthly mean climatological value during the period 2000–2009.

2004] are also used in order to examine the variations in dust aerosols over northwestern India.

[20] Figure 5 shows the daily variation as well as the 10-day moving average of Terra/MODIS Deep Blue AOD_{550} over northwestern India (25°–30°N, 69°–78°E), including Thar Desert, during Jan 2002 – Dec 2003. The results show a pronounced annual AOD variation with large peaks on specific days during late pre-monsoon and monsoon seasons for both years. The Deep Blue AODs over Thar Desert during 2002 and 2003 are consistent with the anomalies observed in the AOD values over the whole of northern India (Figure 4) in July 2002 and May–June 2003. The 10-day moving average exhibits higher annual AODs during July–August in 2002 and May–June in 2003, in close agreement with the deficit of rainfall over northwestern India during these periods. The inset plot in Figure 5 corresponds to the anomaly in AOD values for April–July months of 2002 and 2003 from the climatological mean (2000–2007). Similar to the results observed in Figure 4, the Deep Blue retrievals show positive anomalies of ∼0.3 in July 2002 and ∼0.2–0.25 for May–June 2003. The negative AOD anomaly in July 2003 is also noted, which is similar to those observed in Figure 4. In addition, inter-annual variability in aerosol loading over IGP has also been linked with the QBO by examining zonal winds and tropopause temperature, pressure and height data [*Abish and Mohanakumar*, 2012]. Thus, in addition to the local aerosol emissions, variability in precipitation and dust occurrence, large-scale atmospheric dynamics may play a crucial role in aerosol loading over IGP.

[21] Furthermore, the spatial distribution of AI over south Asia was also examined from the long-term TOMS data set during April–July months of the period 1979–2005 and the respective monthly means for the years 2002 and 2003 (Figure S1 in auxiliary material Text S1).[1] The AI values for the 2002 and 2003 months can be qualitatively compared with the respective climatological means, since as proposed by the TOMS scientific team [*Gautam et al.*, 2009b] any trends after 2001 must be avoided due to larger uncertainties in the data sets (associated with sensor degradation).

[22] The AI values for the studied months are significantly higher than their monthly (1979–2005) mean with the largest differences over Arabian Peninsula, northernmost part of AS, Pakistan and western IGP (Figure S1 in auxiliary material Text S1) i.e., representing the pathways of dust transport into the IGP. The results show that the highest increase of AI occurs during May–June of 2003 and July of 2002 over the arid regions of Arabia, Pakistan and Thar Desert and are, in general, consistent with the areas of the most negative anomalies in precipitation (Figure 2) and highest positive anomalies in MODIS AOD_{550} (Figure 4). The spatial distribution of the enhanced AI indicates a pronounced increase in dust activity and atmospheric aerosol lifetime associated with a widespread pattern stretching from the Arabian Peninsula and Thar Desert, which strongly influences the aerosol field over northern India. In contrast, the southern AS, central-south India and BoB are not influenced. Based on the climatological analysis of aerosol field over northern India, it appears that the enhanced aerosol loading during pre-monsoon and monsoon months of 2002 and 2003 strongly influenced the whole decadal (2000–2009) AOD trend over IGP, likely leading to a decreasing tendency of coarse-mode aerosols, as observed from both MISR and MODIS data [*Dey and Di Girolamo*, 2011; *Kaskaoutis et al.*, 2011a]. Overall, the results from TRMM,

[1] Auxiliary materials are available in the HTML. doi:10.1029/2011JD017314.

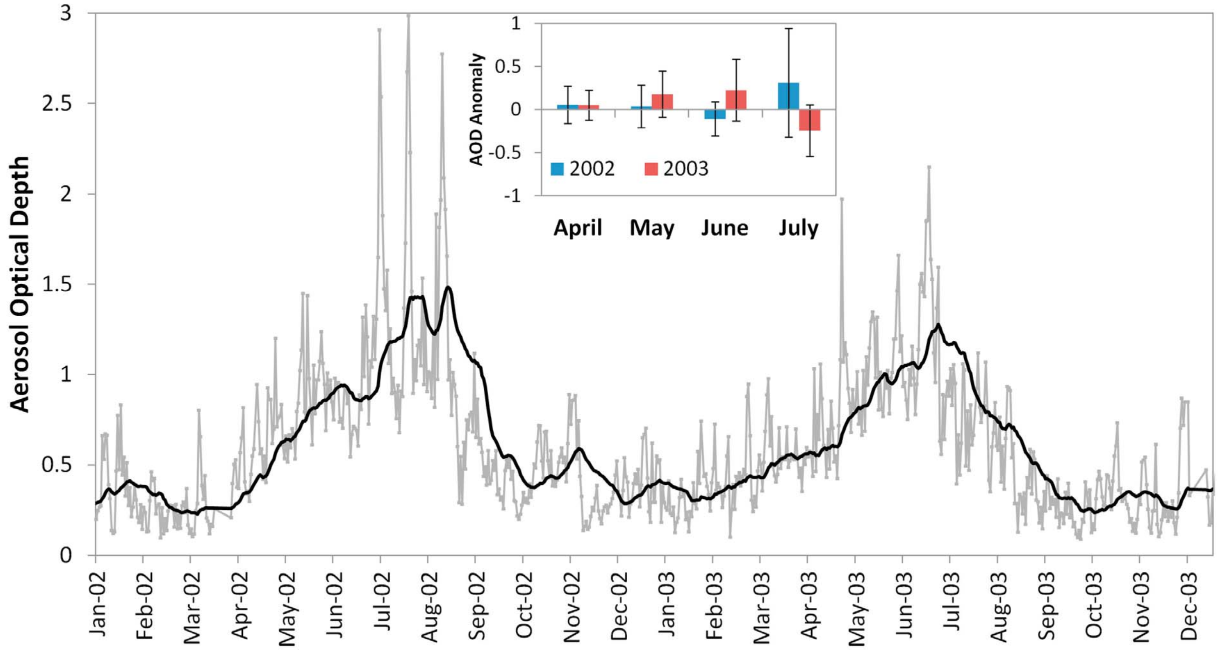

Figure 5. Daily variation of the Terra MODIS Deep Blue AOD_{550} from January 2002 to December 2003 (gray line) averaged over northwestern India (25°–30°N, 69°–78°E). The black line is the 30-day moving average over the period. The inset plot corresponds to the monthly mean Deep Blue AOD anomaly for April, May, June and July during 2002 and 2003 from the monthly climatological mean during the period 2000–2007 with error bars representing 1 standard deviation from the area-averaged mean.

MODIS and TOMS are found to be strongly linked to each other and to the findings of other studies over the region examining the influence of low rainfall and associated meteorological conditions on aerosol optical properties and distribution.

3.3. Modification in Aerosol Properties Over Kanpur and Delhi

3.3.1. Aerosol Optical Depth and Angstrom Exponent

[23] In addition to the analysis of large-scale anomalies in meteorological fields and aerosol distribution over south Asia, the present study further emphasizes on the modification of aerosol optical properties over Delhi and Kanpur, aiming at associating them with the aforementioned dry conditions. The spectral aerosol properties obtained over the two urban locations are analyzed during April–July of 2002 and 2003 relative to their long-term (~10 years) monthly means.

[24] Figure 6 shows the daily mean AOD_{500} (low panel) and $\alpha_{440-870}$ (upper panel) variations over Kanpur AERONET site during April–July of 2002 (red) and 2003 (blue), in comparison with the respective April–July means during the period 2001–2010 (see figure caption for details). The results show higher AODs during the studied months for both years compared to the decadal mean, with frequent peaks (above one st.dev.) mainly in May–June 2003 and July 2002. These peaks, which can be even above 1.5 in several cases, are closely associated with respective lows in α, which are below the minus one standard deviation from the decadal mean indicating increased accumulation of dust loading. The aerosol features are consistent with the drought in July 2002, and during May and beginning of June 2003 that favors frequent dust outbreaks from Thar Desert and accumulation of aerosols over IGP. In general, during the first half of June 2003, the most severe dusty conditions were observed over Kanpur with about 10 consecutive days associated with $AOD_{500} > 0.98$ and $\alpha_{440-870} < 0.17$ [*Prasad and Singh*, 2007b]. Similarly, during July 2002, the presence of larger particulates with considerably high aerosol loading is evident. Majority of daily mean AOD is above 0.6, while the Angstrom Exponent is generally found to be lower than 0.4 indicating accumulation of coarse-mode aerosols in the atmosphere, which otherwise would have been washed out during a normal monsoon period.

[25] The respective daily variation of the AOD_{500} values obtained over Delhi during the period April–July 2002 (Figure 7, left) and 2003 (Figure 7, right) is shown in Figure 7. It is to be noted that all instantaneous measurements are plotted (and not the daily averages), while the 2002–2010 April–July mean along with the standard deviations are also shown. The mean April–July AOD_{500} over Delhi is much larger (0.84 ± 0.41) than that found over Kanpur (0.67 ± 0.31) mainly due to its proximity to the Thar desert. The results show frequent peaks in AOD_{500}, which are much larger during May–June 2003, while the rainy July 2003 period has a limited number of data. With respect to the 2002 season, some extreme AOD values are observed in May–July. Comparable extreme AODs during dust storms over Delhi are also reported by *Pandithurai et al.* [2008] causing large attenuation in solar radiation reaching the surface, while the abundant aerosol loading during April–June 2003 was the subject of surface radiative forcing analysis [*Singh et al.*, 2005]. The enhanced AODs and the several peaks during July 2002 and May–June 2003 over

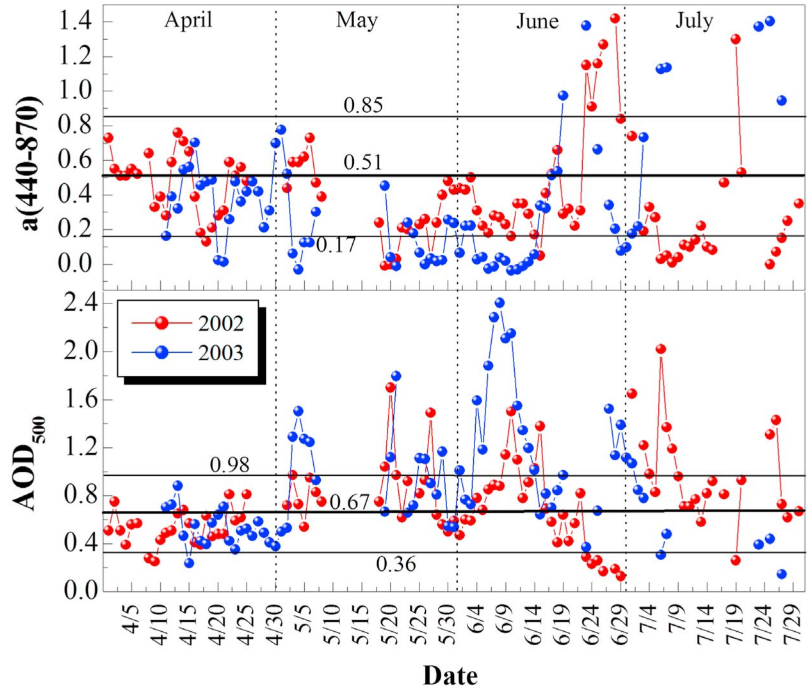

Figure 6. Temporal variation of the daily mean values of (bottom) AOD_{500} and (top) $\alpha_{440-870}$ during the period April–July for the years 2002 and 2003 over Kanpur. The mean (2001–2010) value (bold line) of each parameter for the same period is shown along the upper and lower limits of the one standard deviation from the April–July mean.

both Delhi and Kanpur are consistent with the positive anomalies in AOD_{550} obtained from MODIS over IGP region in the same months (Figure 4) as well as with the respective high TOMS-AI values (Figure S1 in auxiliary material Text S1). It should be noted that the α values over Delhi are much lower during the extremes of AOD suggesting enhanced contribution of coarse-mode dust aerosols.

[26] Furthermore, in order to illustrate the similar transport pathway influencing accumulation of aerosols in the IGP, we show the association of the daily mean AOD_{500} for the overlapping days of observations over Delhi and Kanpur (Figure S2 in auxiliary material Text S1). The results show a high and statistically significant correlation between the two data sets ($r = 0.68$, p value < 0.0001), indicating that the day-to-day variability and peaks of AOD are rather similar over the two sites that are about 400 km apart, further suggesting consistency in the aerosol source and transport pathways. This suggests that the dust outflows from Thar Desert, or

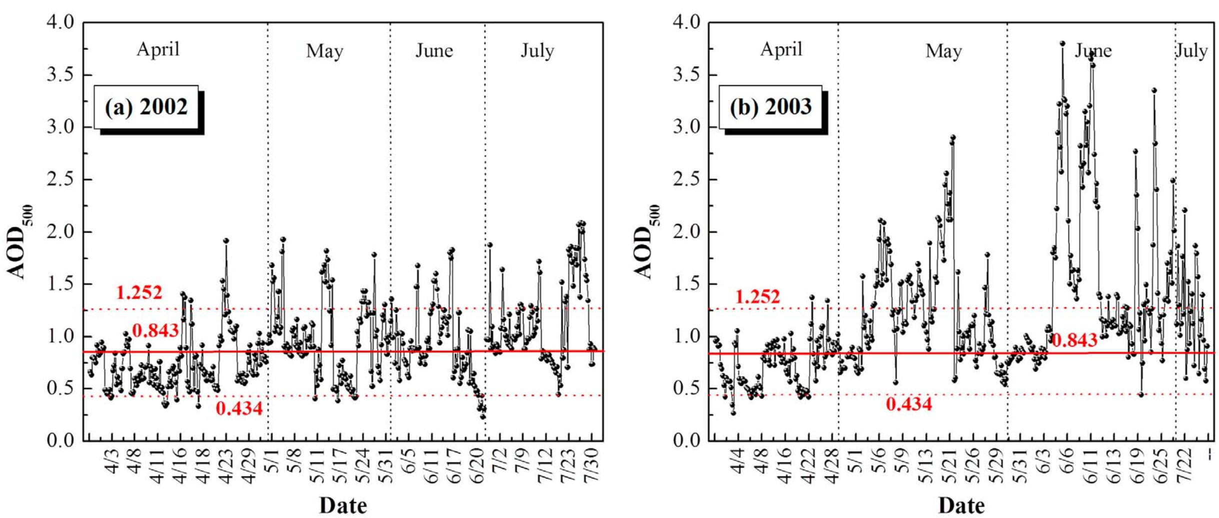

Figure 7. Temporal variation of the observed AOD_{500} values during the period April–July for (a) 2002 and (b) 2003 over Delhi. The mean (2002–2010) AOD value (red bold line) for the same period is shown along the upper and lower limits of the one standard deviation from the April–July mean.

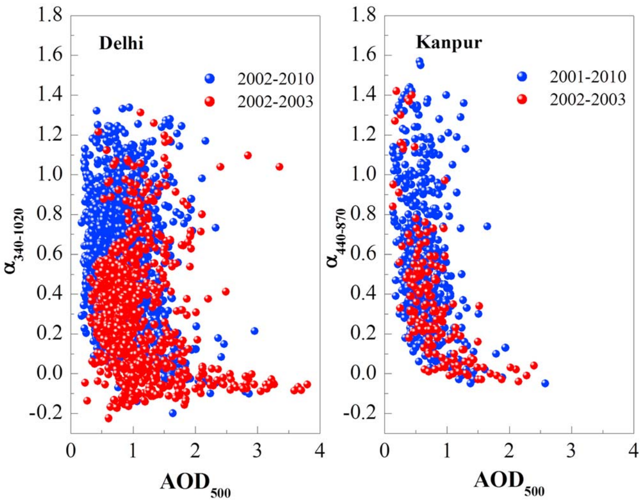

Figure 8. Scatterplot of AOD_{500} versus α values for the months April–July during the period 2002–2003 and for the whole data sets over Delhi and Kanpur.

from long-range transport, influence the western-central IGP region and can affect the daily AOD at both sites. Additionally, back-trajectory analysis for major dust storms observed over Kanpur during pre-monsoon and early monsoon seasons of 2005 [*Prasad and Singh*, 2007b] show that, independently from the source region, majority of air masses traversed over Delhi before reaching Kanpur, with higher AOD over Delhi compared to Kanpur. Similarly, *Jethva et al.* [2005] based on MODIS observations found larger AODs associated with coarse-mode aerosols in western IGP, as the distance from the dust source regions decrease.

[27] The modification of aerosol optical properties in pre-monsoon and monsoon seasons of 2002 and 2003 over IGP can also be seen by the scatterplot of AOD versus α, which provides information about the dominant aerosol types [*Gautam et al.*, 2011]. Figure 8 presents the AOD versus α scatterplot over Delhi and Kanpur, separating the entire available April–July data sets into two groups, (i) April–July of 2002 and 2003 and (ii) the remaining years. At both locations, the 2002–2003 period exhibits a shift of the data points toward lower α and higher AOD particularly for the lowermost α cases, thus indicating increased frequency of aerosols classified to the dusty type [*Kaskaoutis et al.*, 2007; *Ogunjobi et al.*, 2008]. It is therefore concluded that the examined period is considered as one of the most dust-laden seasons during the last decade over IGP.

[28] Further, we examined modification of the aerosol optical properties at Kanpur AERONET station using the identification scheme first proposed by *Gobbi et al.* [2007]. This scheme combines α and its spectral variation ($d\alpha$) with the radius of fine-mode particles (R_f) and the fine-mode fraction (η) as the grid parameters in grouped AOD. Thus, for the change in α, $d\alpha$ pairs with increasing AOD valuable information about several aerosol modification processes can be revealed. In the present case (Figure 9) the AOD groups are examined separately for April–July of 2002 and 2003 (red group) and for the respective months during the period 2001–2010 (blue group) focusing on the changes in α versus $d\alpha$ pattern between the two groups. The modification processes over Kanpur on annual and seasonal basis are well documented by *Gobbi et al.* [2007] and *Wang et al.* [2011], respectively. Figure 9 clearly shows presence of two aerosol types. However, for nearly the whole data set the η values are below 70% suggesting clear dominance of coarse-mode aerosols over the region during April–July period. The "blue" group shows, in general, a shift toward the origin (α, $d\alpha = 0$) with increasing AOD along a nearly constant R_f of about 0.12 μm and continuously decreasing values of η, thus suggesting negligible variation in fine-mode radii and a

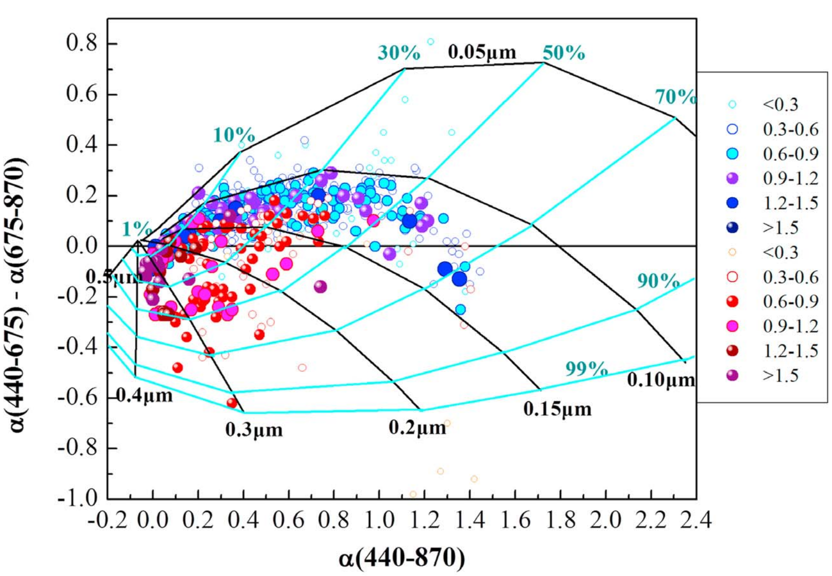

Figure 9. Correlation of α(440–870) with $d\alpha$ ($\alpha_{440-675} - \alpha_{675-870}$) values over Kanpur for the period April–July of 2001–2009 (blue) and for the same period of the years 2002 and 2003 (red) for different AOD classes noted at the legend. Note the large changes in the second period indicating extremely large contribution of dust as AOD increases.

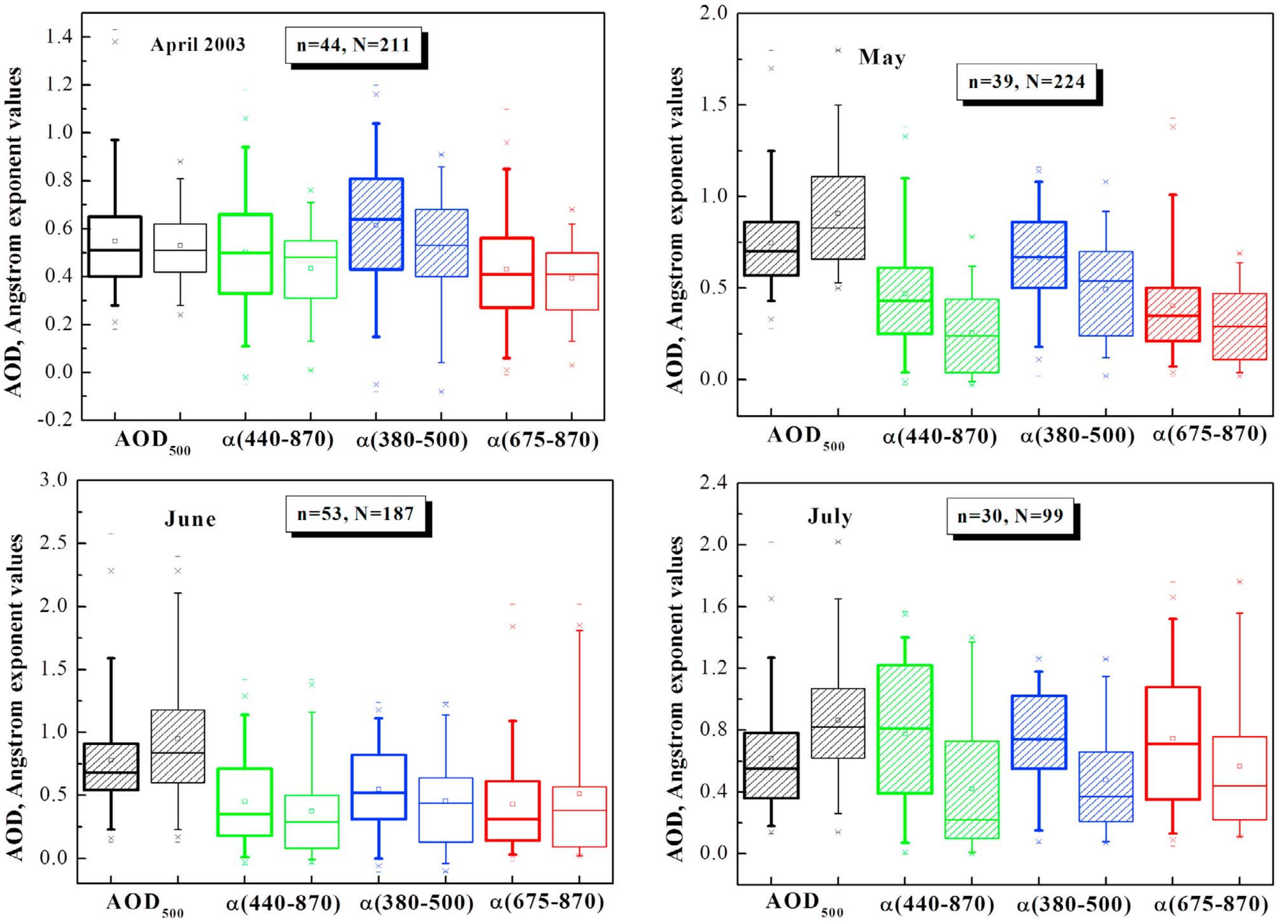

Figure 10. Box charts for AOD_{500} (black), α(440–870) (green), α(380–500) (blue) and α(675–870) (red) at Kanpur AERONET site for May–July of 2001–2010 (bold borders) and for the same months in 2002–2003. The statistically significant differences between the means of the two groups at 95% confidence level are defined with the filled patterns. The number of observations for each group (n for 2002–2003 months, N for the whole period) is also provided.

significant increase in coarse-mode fraction; these conditions are characteristic for enhanced dust contribution at higher AODs. The "red" group exhibits, in general, lower α values (<0.8), also associated with $\eta < 50\%$ and $R_f > 0.15$ μm indicating larger dominance of coarse-mode fraction and increase in fine-mode radius. Especially for the cases with $AOD_{500} > 1.2$, the η is below 30% and the $R_f > 0.3$ μm suggesting nearly absence of fine mode. Opposite to the "blue" group, the increase in AOD for the "red" group is not associated to the modification processes, i.e., hydration, cloud contamination, coagulation [*Gobbi et al.*, 2007], or to those revealed via theoretical Mie calculations for desert dust aerosols [*Yoon et al.*, 2011] or even to those measured over arid environments in Sahara and Middle East [*Basart et al.*, 2009]. Therefore, these cases of extreme high AOD_{500} (>1.2) associated with $\eta < 30\%$ and large (>0.3 μm) R_f values may constitute a specific category occurring under severe dust events.

[29] The statistical significance of the changes in the aerosol properties observed during the months April–July for 2002 and 2003 from the monthly means during the period 2001–2010 is further examined over Kanpur by applying statistical tests (t-test). In this respect, the AOD_{500} (black), $\alpha_{440-870}$ (green), $\alpha_{380-500}$ (blue) and $\alpha_{675-870}$ (red) data are plotted in box charts (Figure 10) for the months April–July (see Figure caption for details). Therefore, the aerosol properties are grouped into two periods and the statistically significant differences in these two groups are examined. The values of $\alpha_{380-500}$ and $\alpha_{675-870}$ are included in the analysis since they provide valuable information about the modification in the fine-mode radius and in the coarse-to-fine mode ratio, respectively [*Reid et al.*, 1999; *Schuster et al.*, 2006].

[30] In April, the aerosol properties are not statistically differentiated, except for the $\alpha_{380-500}$ that exhibits lower values in April 2002–2003, suggesting a shift toward larger fine-mode radius. Lower values of $\alpha_{440-870}$ are also observed for 2002–2003 compared to the decadal mean, while the AOD_{500} is rather similar in consistency with the low changes observed by MODIS over the region (Figure 4). In contrast, May of 2002 and 2003 exhibits much higher AOD_{500} and lower alphas, which are statistically different from the decadal means at 95% confidence level. These changes indicate the large influence of coarse-mode dust aerosols during the late pre-monsoon of 2002 and 2003 and can modulate the aerosol trends during the whole

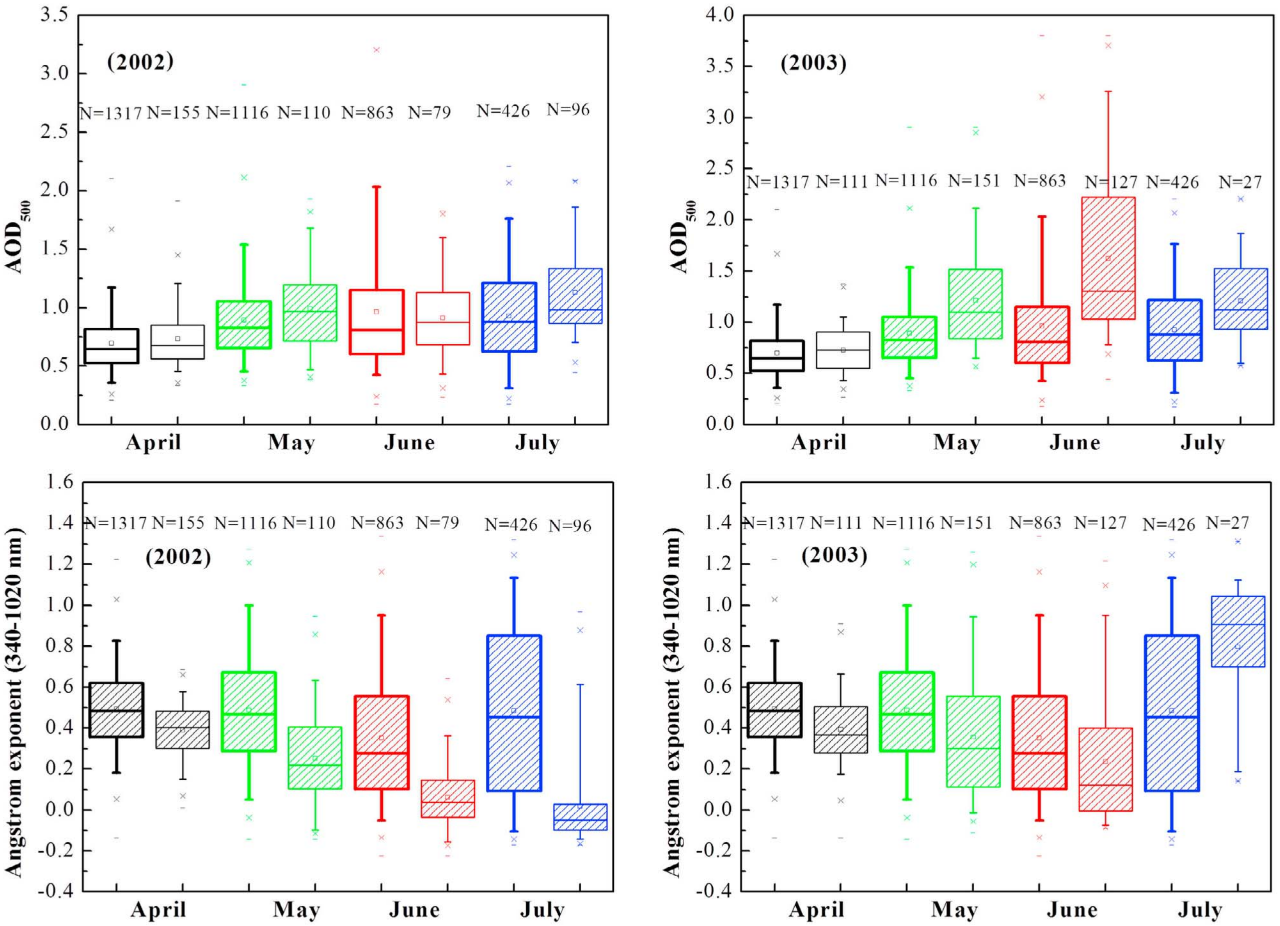

Figure 11. Box charts of AOD_{500} and α(340–1020) values over Delhi for April–July of 2002–2010 (bold borders) and 2002–2003. The statistically significant differences between the means of the two groups at 95% confidence level are defined with the filled patterns. The number of observations for each group is also provided.

decade. It is to be noted that the main contributor to the large AOD_{500} and low alphas is May 2003 rather than 2002, in close agreement with MODIS observations (Figure 4). The extremely large AOD_{500} peaks during June 2003 modulate the overall large increase in 2002 and 2003 June period, while no statistical difference occurs for the alpha values, although they were found to be much lower during June 2003. However, larger values of α during June 2002 smooth the mean values. The most contrasting month during the years 2002 and 2003 is July, with extremely drought conditions in 2002 and normal rainy monsoon in 2003. The July data set mainly corresponds to observations in the dry and cloudless July of 2002 (22 out of 30 cases). Thus, in consistency with the large % increase in MODIS AOD_{550} and TOMS-AI, the mean July AOD_{500} is much larger than the decadal mean. The increase in AOD_{500} is closely associated with decrease in alphas (statistically significant decline for $\alpha_{440-870}$ and $\alpha_{380-500}$) suggesting enhanced presence of dust aerosols over Kanpur.

[31] The respective analysis over Delhi (without including α at shorter and longer wavelengths due to limited number of spectral AODs) shows more or less similar results to Kanpur (Figure 11). Thus, April does not exhibit statistically significant difference in AOD_{500}, opposite to that observed for May and July of 2002 and for May–June–July of 2003. The only inconsistency that is observed with Kanpur data and MODIS retrievals is the statistically significant higher value in July 2003; however, the small data set in this month (27), also limited on 5 days of observations may not be representative for the monthly mean and causes bias to the statistical retrievals. Regarding the $\alpha_{340-1020}$ values they are significantly declined during 2002–2003, with the exception of the larger values in July 2003. The summary of the results, show that the modifications in aerosol properties over Delhi during late pre-monsoon and monsoon months of 2002 and 2003 is more intense than those over Kanpur, suggesting larger influence of dust optical properties. The analysis shows that the mean values in these months can modulate the decadal mean and, this is the reason for the declining AOD trend during April–July over IGP with higher decreasing intensity over the western part located closer to the dust source regions [*Kaskaoutis et al.*, 2011a].

3.3.2. Aerosol Size Distribution and Single Scattering Albedo

[32] In addition to AOD and α values, the AERONET almucantar retrievals (CSD and spectral SSA) are further

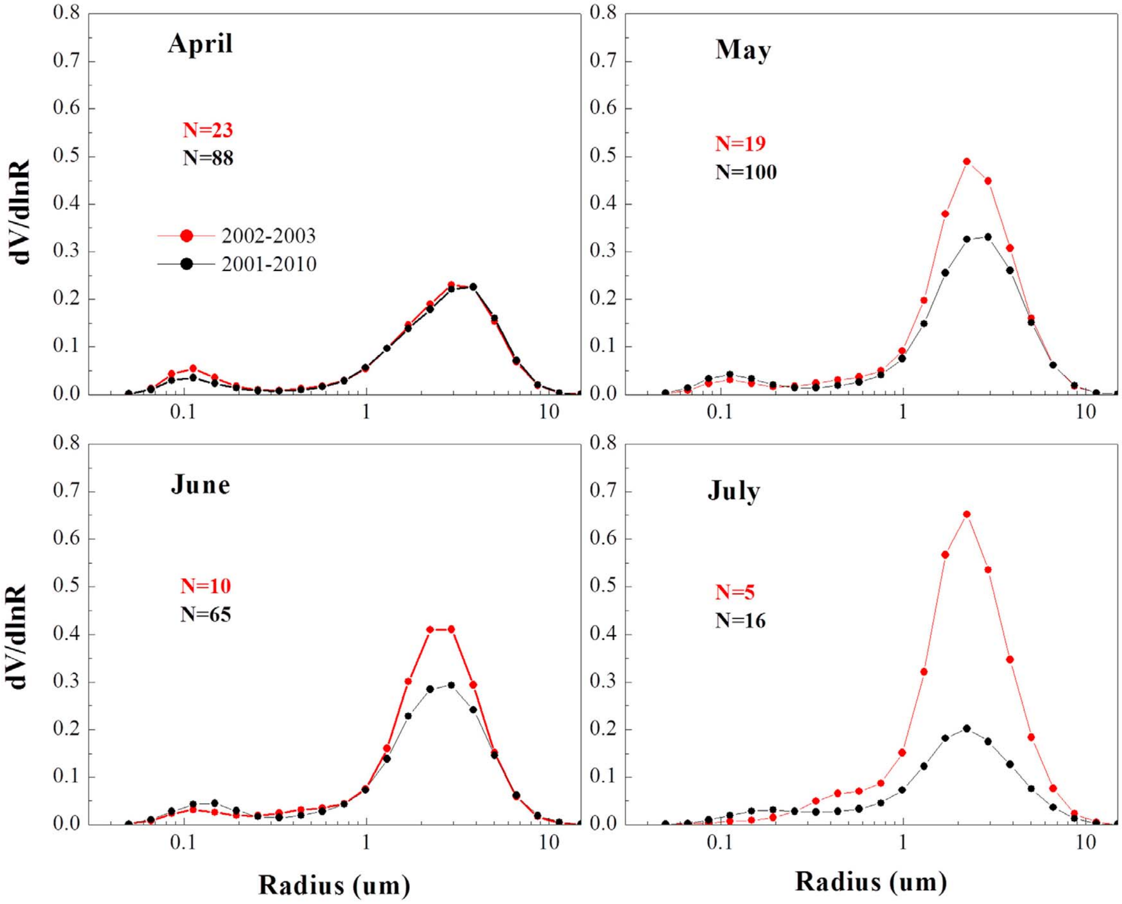

Figure 12. Columnar size distributions (CSD) at Kanpur AERONET site for April–July months of 2002–2003 and for the respective months during the period 2001–2010. The available number of almucantar retrievals for each month and period is given in each graph.

analyzed over Kanpur focusing on modifications during April–July of 2002–2003 from the monthly decadal means. Figure 12 shows the monthly mean CSDs for 2002–2003 and 2001–2010. A typical bi-modal lognormal distribution, with a pronounced peak in the coarse mode, is observed for all months characteristic to the dust-laden environment over northern India. The 2001–2010 mean CSDs suggest strong dust influence during late pre-monsoon (May–June) and a significantly reduced coarse-mode influence in July associated with aerosol washout process. For the 2002–2003 period, we find that month of April does not exhibit any significant difference in the CSDs between the two periods, except from an increase in fine-mode during 2002–2003, which is not observed in α values (Figure 10). However, it is to be noted that the retrievals of CSDs are fewer than spectral AOD and α and, therefore, cannot be considered as absolutely representative of the daily and monthly mean; thus some biases may exist. Furthermore, the uncertainty of ~15% in CSD retrievals should be considered when comparing the results. Despite these difficulties, the CSDs in May, June and July present large differences during 2002–2003 compared to the decadal mean, mainly showing presence of larger coarse-mode fraction and a shift toward larger radius for the fine mode. Especially during June and July of 2002 (there is lack of data for these months in 2003), the fine-mode fraction tends to absent, thus highlighting the strong contribution of the coarse-mode desert dust aerosols [*Eck et al.*, 2005]. The resulting coarse-mode peak for July (>0.6 $\mu m^3/\mu m^2$) 2002, is significantly larger than the decadal mean value (~0.2 $\mu m^3/\mu m^2$). These modifications have a clear signal in the higher AODs and lower alphas during 2002–2003 (Figure 10).

[33] The enhanced loading of coarse-mode dust aerosols during monsoon of 2002 and late pre-monsoon of 2003 over IGP is also clearly detected by the spectral SSA values over Kanpur (Figure 13). In all months, the SSA values increase with the wavelength, thus indicating coarse-mode dust aerosols [*Dubovik et al.*, 2002; *Russell et al.*, 2010] associated with greater absorption at shorter wavelengths (e.g., 440 nm). Additionally, the SSA gradually increases from April to July suggesting presence of aerosols of more scattering type. Moreover, the period 2002–2003 exhibits a positive gradient in spectral SSA toward longer wavelengths, thus indicating enhanced presence of dust. On the other hand, at 440 nm, the SSA values in both periods are similar or slightly lower for the 2002–2003 period, that may be due to increased dust absorption in the UV [*de Graaf et al.*, 2005]. Despite the limited number of spectral SSA data and the uncertainties in almucantar retrievals, the results indicate strong dust optical properties and spectral absorption characteristics during 2002–2003.

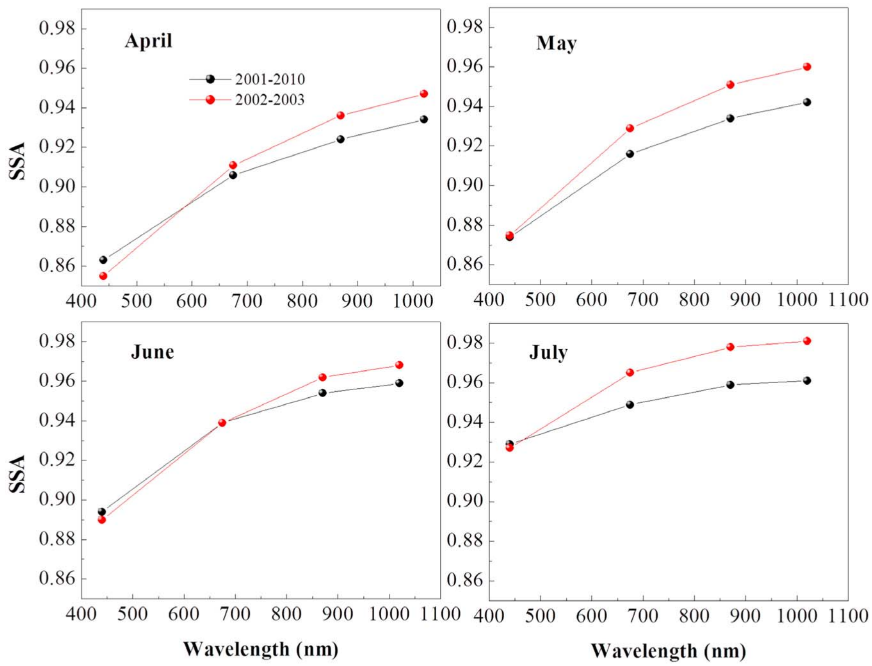

Figure 13. Spectral variation of Single Scattering Albedo (SSA) over Kanpur in April, May, June and July for the years 2002–2003 (red) and for the period 2001–2010 (black).

3.4. SPRINTARS Simulations

[34] The dust-AOD anomalies in April–July of 2002 and 2003 from the monthly mean values during the period 2000–2008 are shown in Figure 14, as simulated via SPRINTARS model over south Asia. Despite the coarser spatial resolution of SPRINTARS compared to MODIS and TOMS, and the different periods that considered for the retrieval of the anomalies, the model simulations are in general agreement with the results obtained from satellites. Thus, during April the AODs in 2002 and 2003 are similar to the 2000–2008 mean, without pronounced spatial heterogeneity. In general agreement with satellite observations, the simulated dust AODs are much larger (by 0.3–0.5) during July 2002 and May–June 2003 over northwestern arid India, whereas over the southern latitudes and over BoB the anomaly is negligible. The SPRINTARS results suggest that the increase in dust AOD over northwestern India in July 2002 and May–June 2003 is mainly attributed to local emissions from Thar desert and not to increase in long-range dust transport. A deficit in precipitation was observed over northwestern India, which seems to be well simulated by the model.

4. Conclusions

[35] The present study focused on examining the influence of rainfall anomalies (deficit) and prolonged dry conditions during the monsoon 2002 and pre-monsoon 2003 periods on the aerosol characteristics over Indian sub-continent in general, but in particular over the IGP. During July 2002, India experienced the worst drought conditions in the past 50–60 years and subsequent persistence of prolonged dry conditions, especially over northern parts including the Thar Desert and the IGP region. A synergy of meteorological and aerosol data from satellite sensors and ground-based measurements as well as chemical transport model SPRINTARS simulations were utilized for this study. The NCEP/NCAR meteorological data showed positive anomaly in MSLP and geopotential height over AS and most of India during July 2002 (mainly) and May–June 2003 (secondarily) implying weakened southwest monsoon over India. Especially, July 2002 was characterized by erratic monsoon conditions over Indian sub-continent with deficit of rainfall particularly over the northwestern arid regions. Considerably reduced rainfall also occurred during the pre-monsoon season (May–June) of 2003 as observed by TRMM data. The deficit of rainfall in these months may have led to enhanced dust aerosols and prolonged lifetime over northern India and IGP, as opposed to a typical aerosol washout scenario during monsoon season. MODIS and TOMS satellite retrievals showed increased values of AOD and AI, respectively over northwestern arid India during July 2002 and May–June 2003 from their long-term mean, while ground-based aerosol measurements over Delhi and Kanpur revealed several peaks of AOD during the above months associated with frequent and intense dust events. The accumulation of dust aerosols over IGP during July 2002 and May–June 2003 strongly modified the aerosol properties over the region by inducing a significant increase in AOD, decrease in α, shift in the aerosol size distributions toward larger coarse-mode fraction and higher particle radius, and an increase in the SSA values (more scattering) at longer wavelengths.

[36] Detailed analysis presented here suggests a strong cause-and-effect linkage between the deficit of precipitation and subsequent increased dust aerosols that influence the dynamics of aerosols and climatic conditions of northern India, thus highlighting an association between monsoon system and aerosol field over south Asia that may further have direct (radiative) and indirect (cloud microphysical) implications during the monsoon season. The SPRINTARS simulations over south Asia were in general agreement with

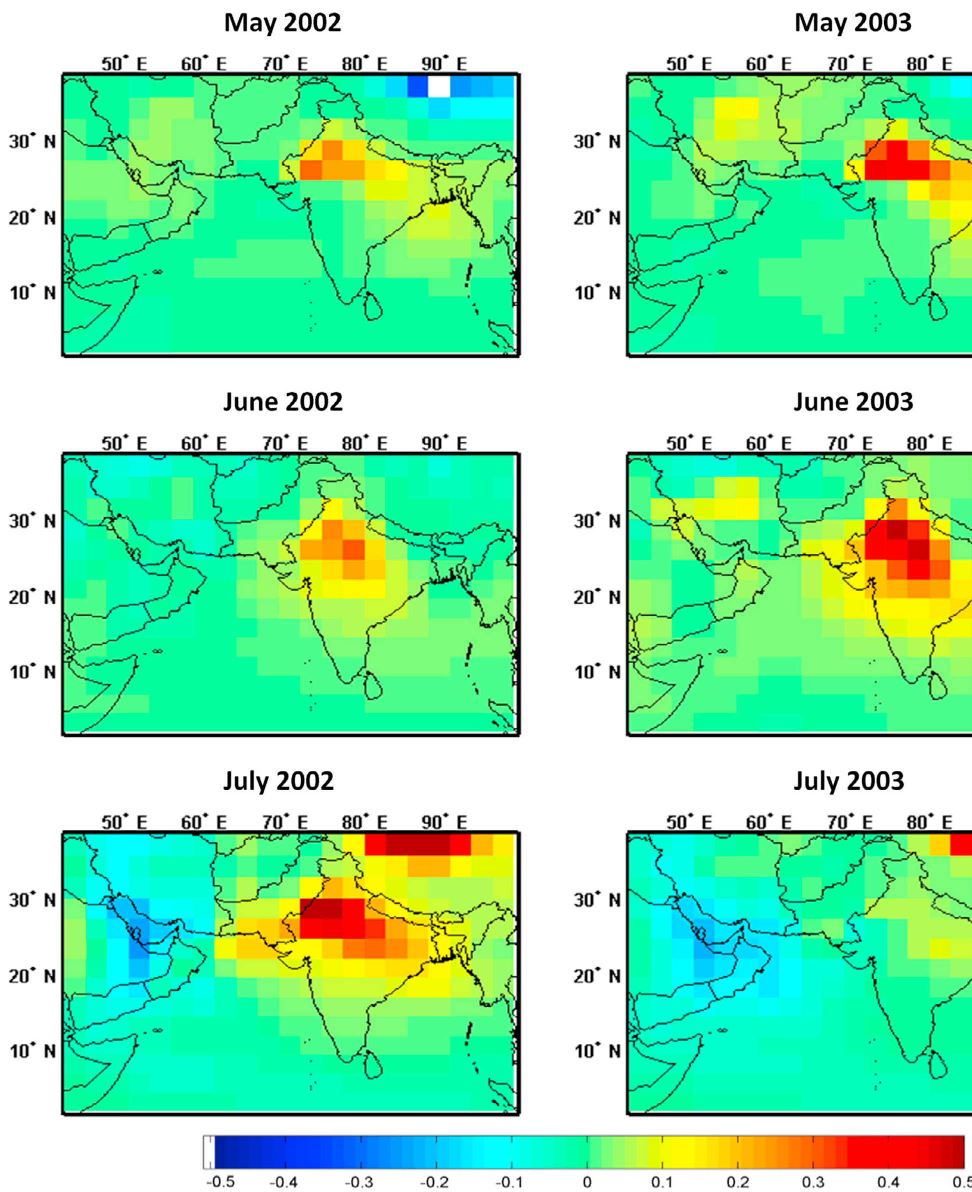

Figure 14. Anomaly in dust AOD over south Asia via SPRINTARS simulations during April–July of 2002 and 2003 from the monthly mean climatological situation 2000–2008.

the satellite observations suggesting much higher dust AOD over northern India during July 2002 and May–June 2003 compared to the mean values during the period 2000–2008.

[37] **Acknowledgments.** IIT Kanpur AERONET is operational as of January 2001 after the joint agreement by IIT Kanpur and NASA. The agreement was initiated by one of the authors (R.P.S.), our sincere thanks to the AERONET team for making the data available. The authors would like to thank the TRMM science data support team (past and present) for processing data via the Giovanni website (http://giovanni.gsfc.nasa.gov/) as well as the MODIS and TOMS science teams for providing the AOD and AI data sets. The NCEP/NCAR Reanalysis team is also gratefully acknowledged for providing the meteorological data. The SPRINTARS calculations were performed by using National Institute for Environmental Studies (NIES) supercomputer system (NEC SX-8R/128M16). We would also like to thank many developers for MIROC AGCM and SPRINTARS. We thank the three anonymous reviewers for useful comments that helped to improve an earlier version of the manuscript.

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