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Two contrasting dust-dominant periods over India observed from MODIS and CALIPSO data

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[1] Each year, prior to the onset of the Indian Summer Monsoon, the Gangetic Plains (GP), bounded by the high-altitude Himalayan mountains, are strongly influenced by the transport of dust outbreaks originating in the northwestern desert in India (known as the Thar Desert). Dust particles constitute the bulk of the regional aerosol loading which peaks annually during the pre-monsoon season. This paper integrates observations from space-borne sensors, namely MODIS and CALIPSO, together with ground sunphotometer measurements, to infer dust loading in the pre-monsoon aerosol build-up over source and sink regions in northern India. Detailed aerosol characterization from the synergetic observational assessment suggests that the two pre-monsoon seasons of 2007 and 2008 were strikingly contrasting in terms of the dust loading over both the Thar Desert and the GP. Further analysis of aerosol loading and optical properties, from the entire record of MODIS and sunphotometer observations, reveals that the 2007 pre-monsoon season was an unusually weak dust-laden period. Our findings suggest the plausible role of the immediately preceding excess winter monsoon rainfall in the suppressed dust activity during the 2007 pre-monsoon season. **Citation:** Gautam, R., Z. Liu, R. P. Singh, and N. C. Hsu (2009), Two contrasting dust-dominant periods over India observed from MODIS and CALIPSO data, *Geophys. Res. Lett.*, *36*, L06813, doi:10.1029/2008GL036967.

1. Introduction

[2] Tropospheric aerosols significantly influence the Earth's radiation budget by scattering as well as absorbing solar radiation and are considered to be one of the least understood components of the global climate system [*Ramanathan et al.*, 2001; *Haywood and Boucher*, 2000; *Bellouin et al.*, 2005]. Mineral dusts are a major contributor to the aerosol loading in the troposphere influencing the seasonal variability of the aerosol optical properties and the regional-to-global radiative forcing [*Tegen and Lacis*, 1996]. Through their influence on cloud microphysical properties and cloud lifetime [*Rosenfeld et al.*, 2001] as well as perturbations to the radiative energy balance, recent studies suggest that mineral dust may also potentially induce changes in the global hydrological cycle [*Miller et al.*, 2004], especially over the Indian subcontinent which receives the bulk of the annual precipitation during the summer monsoon season [*Lau et al.*, 2006].

[3] Over India, dust storms are a major climate phenomena frequently originating in the north-western region of the Thar Desert, which has long been recognized as a primary source of atmospheric soil dust [*Middleton*, 1986]. Dust activity starts in March–April and peaks in May, i.e., prior to the onset of the Indian Summer Monsoon with strong pre-monsoon westerly winds transporting dust particles into the alluvium of the densely-populated Gangetic Plains (GP) [*Middleton*, 1986; *Prospero et al.*, 2002]. The towering Himalayas form a barrier to the passage of dust storms, resulting in the accumulation of dusts, largely over the foothills of the Himalayas and the GP. As a result, the atmospheric column aerosol loading during the pre-monsoon season is highest over the GP on an annual basis [*Singh et al.*, 2004] combined with the heavy anthropogenic pollution concentrated over this region [*Singh et al.*, 2004; *Gautam et al.*, 2007]. Although detailed studies of the influence of enhanced dust loading have been carried out, however they have been restricted to a single point location in the GP using ground radiometric measurements [*Dey et al.*, 2004; *Singh et al.*, 2004; *Prasad and Singh*, 2007]. Further, the inter-annual variations of the contribution of dust to the net atmospheric aerosol loading over the source as well as over the transported regions in the GP are not well understood.

[4] Here, using an integrated approach of space-borne observations from the Moderate Resolution Imaging Spectrometer (MODIS) as well as from the recently launched Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) instruments, we characterize the dust loading over the source region and its transport into the GP, in conjunction with detailed information from ground radiometric measurements. This synergetic assessment over the Indian subcontinent, particularly over the northern region, focuses on the two immediate pre-monsoon seasons of 2007 and 2008 which are found to be strikingly contrasting in terms of the contributions of dust in the net atmospheric regional aerosol loading. The pre-monsoon aerosol loading and optical properties were further investigated in the entire record of MODIS and sunphotometer measurements suggesting an exceptionally weak dust-laden pre-monsoon period of 2007. Plausible role of the record high rainfall, during the immediately preceding winter season, in the suppressed dust activity is investigated and presented in the paper.

2. Data

[5] We used the second-generation Collection 5 (C005) Level 2 MODIS Aerosol Optical Depth (AOD) data from

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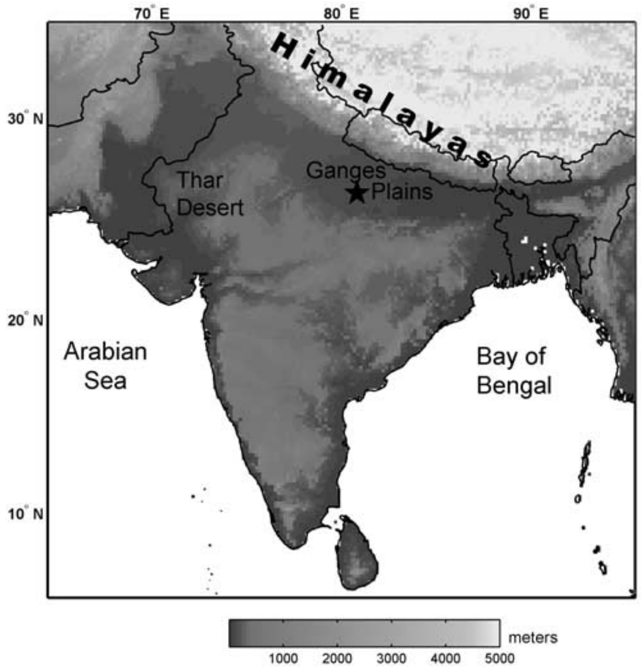

Figure 1. Terrain of the Indian subcontinent: valley-type topography of the Gangetic Plains bounded by the high-altitude Himalayas to the north. Star denotes the location of the sunphotometer at Kanpur in the GP.

Aqua satellite. The C005 aerosol products are an improvement over the previous MODIS aerosol product (C004) [*Levy et al.*, 2007]. However, the C005 algorithm follows a dark-target approach retrieving aerosols over vegetated and oceanic surface with gaps over bright surfaces such as deserts. Therefore, in addition to the C005 aerosol product, we utilize aerosol loading information derived from the MODIS Deep Blue algorithm which retrieves global aerosol information over land including bright surfaces [*Hsu et al.*, 2004]. The pixel size of the Level-2 MODIS swath AOD products is 10*10 km. These datasets were binned into a quarter degree uniform spatial resolution grid and were finally averaged to represent the composite aerosol loading over the Indian subcontinent.

[6] This study also uses observations from CALIPSO that provide global vertically-resolved measurements of atmospheric aerosols. With its capability of depolarization measurements, CALIPSO can also easily discriminate dust from other types of aerosols [*Liu et al.*, 2008]. We use the Level 2 (version 2.01) data product consisting of optical and physical properties of the detected aerosol layers. In addition to the standard AOD retrieval, we have further applied a data filtering criteria (C. Kittaka et al., Intercomparison of the CALIPSO and MODIS aerosol optical depth, manuscript in preparation, 2009) to screen out some low confident retrievals, during heavy aerosol loading conditions (optical depths > 2) and/or when large uncertainties due to noise and incorrect correction for the attenuation of overlying layers may exist. This is alleviated by adjusting the lidar ratio (or, extinction to backscatter ratio) during the retrieval to maintain the retrieval stability and also by screening out profiles that have an anomalous high Integrated Attenuated Backscatter value. Along with space-borne observations, we also use ground measurements of aerosol properties from a CIMEL sunphotometer over Kanpur in central GP, as part of the Aerosol Robotic Network (AERONET) project [*Holben et al.*, 1998].

3. Results

[7] Figure 1 shows the terrain elevation of the Indian subcontinent. The valley-type topography of the GP is bounded by the elevated Himalayan Mountains to its north. The CIMEL sunphotometer is deployed at Kanpur (26.5°N, 80.2°E) in central GP. Figure 2 shows the composite

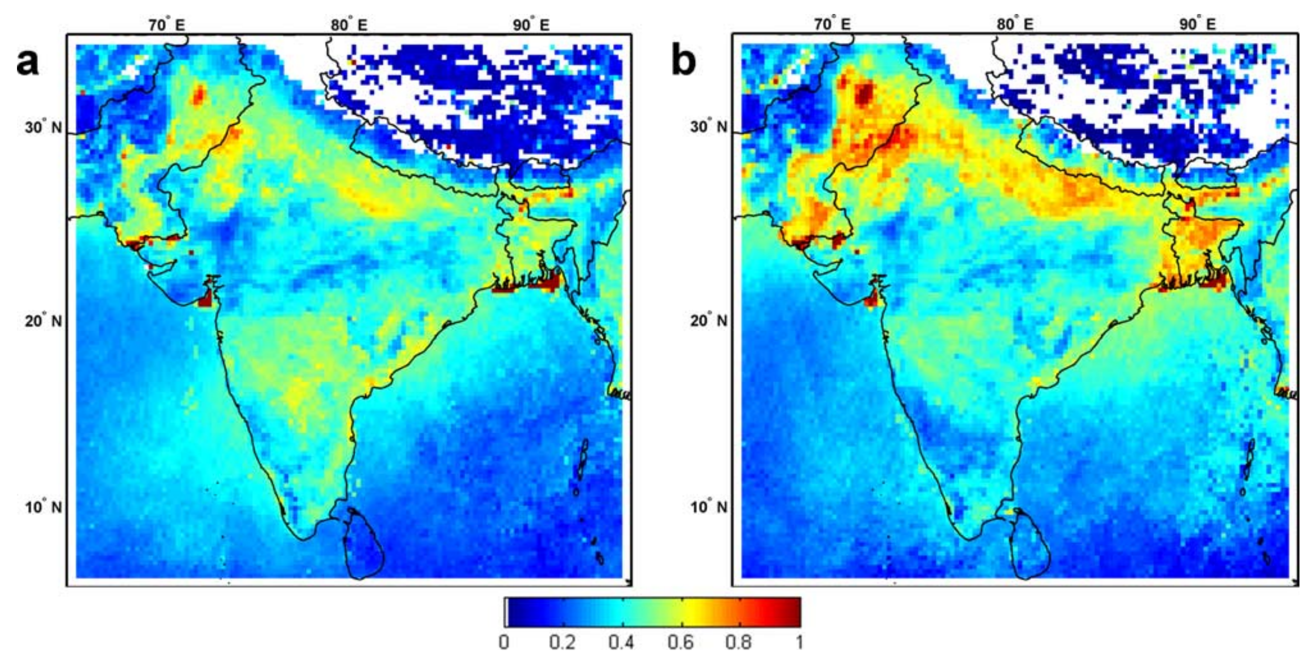

Figure 2. Composite Aqua MODIS aerosol optical depth from Dark-Target and Deep Blue aerosol products over India during the pre-monsoon season (MAM) of (a) 2007 and (b) 2008.

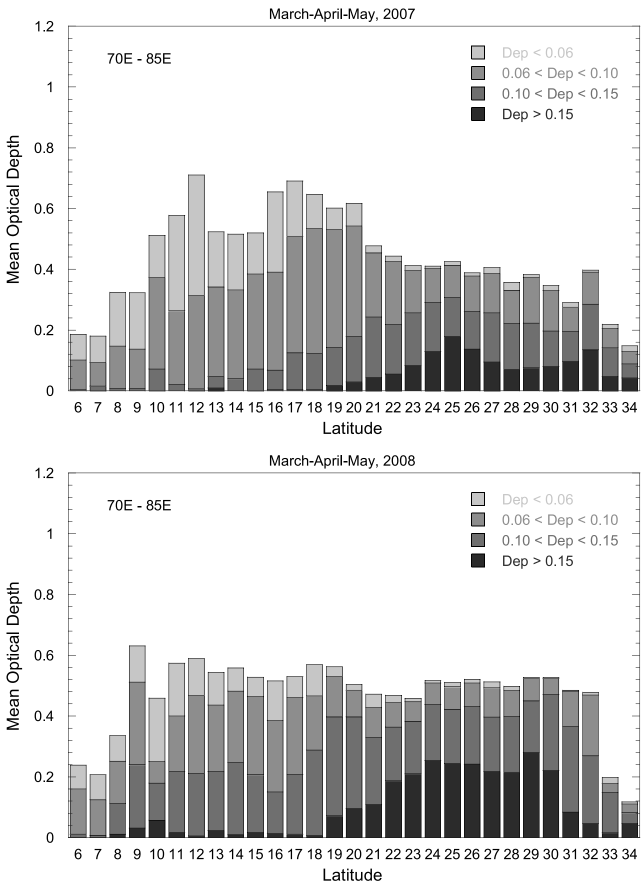

Figure 3. Latitudinal profile of mean aerosol optical depth over India, restricted within 70–85°E, during (a) MAM 2007 and (b) MAM 2008 using CALIPSO aerosol layer product with depolarization ratios (separated in four bins) indicated by different shades in the vertical bars.

MODIS dark-target and Deep Blue AOD representing the mean of daily Level-2 data. A significant difference in the magnitude of the net aerosol loading is discernible between the pre-monsoon seasons (March–April–May, or MAM) of 2007 and 2008. Although, the patterns of aerosol loading are similar over the two periods, however, the entire GP as well as the Thar Desert (69–75°E, 25–29°N) are characterized by enhanced aerosol loading in MAM08 compared to the previous year. The mean optical depths over the Thar Desert are 0.46 and 0.6 during the pre-monsoon periods of 2007 and 2008, respectively. A null hypothesis test was performed on the data corresponding to the desert region to obtain the significance of changes in aerosol loading between the two periods. A two-tailed *t*-test over the two samples indicates that the changes in aerosol loading are significant at 99% confidence interval. Since May is the peak month of dust activity as discussed in section 1, we find that there is an increase of over 80% in the aerosol loading over the Thar Desert, while the AOD over the GP is found to increase by about 30% compared to May 2007. The enhanced aerosol loading is also observed at elevated altitudes (>3 km) over the foothills of the Himalayas resulting in a significantly higher monthly mean value of 0.6 compared to smaller AOD of 0.3 (a factor of two increase).

[8] Detailed analysis of aerosol optical properties in central GP shows significant influence of coarse-mode particles in the enhanced aerosol loading in MAM08. Majority of aerosol measurements in MAM08 are associated with angstrom exponent (α, which is a first-order indicator of the size of aerosol) less than 0.5, while on the other hand, MAM07 is dominated by fine-mode aerosols with α often greater than 0.6 and about 35% of the entire MAM07 sample associated with values greater than 0.8 (Figure S1).[1] Mean α during MAM08 (and May 2008) is found to be 0.4 (0.5) compared to higher values of 0.7 (0.8) during 2007. Also, the spectral behavior of AOD during the pre-monsoon season of 2008 appears to be relatively flat in nature with ~25% increase in AOD at 870 nm and 1020 nm, suggesting greater extinction of light at longer wavelengths due to higher concentration of coarse particles, compared to the 2007 pre-monsoon season.

[9] In addition to the spectral behavior of AOD and the associated wavelength exponent, the aerosol size distribution can also be used to infer the size of particles. The pre-monsoon aerosols are characterized by a bi-modal log-normal size distribution, highest in the coarse mode with mean values of 0.08 $\mu m^3/\mu m^2$ and 0.35 $\mu m^3/\mu m^2$ during MAM07 and MAM08 (quadruple increase in 2008), respectively (Figure S1). The peak of the MAM07 size distribution in coarse-mode is so low that it is almost equal to that of its fine-mode peak centered on 0.14 μm radius.

[10] The present study also utilizes CALIPSO lidar observations, compiled over India, to characterize the pre-monsoon aerosol variations in the two years. Since the western part of India is influenced by greater dust contribution, we restricted our analysis to the 70–85°E area to focus on the dust source and transport. Latitudinal mean AOD from CALIPSO indicates ~40% increase in aerosol loading over northern India during MAM08 compared to 2007 (Figure 3). Again, this difference is underscored during the peak dust activity month of May, during when the mean AOD over northern India is about 1 in 2008 compared to the mean value of 0.6 in 2007.

[11] In order to further corroborate the contrast in dust loading, we use volume depolarization ratios (VDR) derived from CALIPSO backscatter measurements [*Liu et al.*, 2008]. VDR is indicative of the type of particles and can be effectively used to discriminate spherical aerosols (such as sulfate) with non-spherical (such as dust) particles. The VDR is defined as the ratio of the perpendicular and parallel components of the attenuated backscatter signal. Higher VDR suggests greater amount of non-spherical particles (in cloud-free conditions). Although smoke and pollution aerosols contain non-spherical soot particles, the depolarization ratio for these aerosol types is normally small because of the small size of the soot particles. The VDR values from CALIPSO for smoke aerosols over central and southern Africa are generally smaller than 6% with a typical value of 2–3% [*Liu et al.*, 2008].

[12] The mean optical depths over India were grouped in four different bins (Figure 3), based on VDR values vis-à-vis inferring the contributions of different level of dust loading in the net aerosol loading. In MAM08, about 50% AOD

[1] Auxiliary materials are available in the HTML. doi:10.1029/2008GL036967.

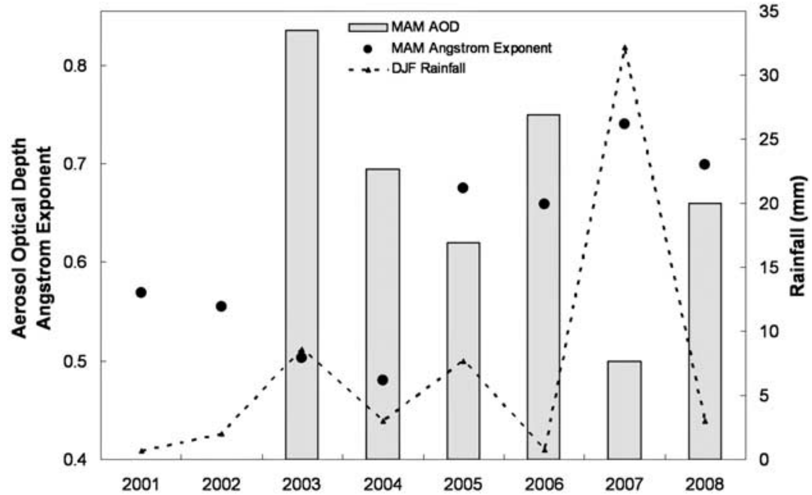

Figure 4. Inter-annual variations of the mean AOD (vertical bars) in MAM over the Thar Desert from Aqua MODIS Deep Blue product, Angstrom Exponent in MAM from 2001 to 2008 obtained from sunphotometer measurements in central GP (black dots), and winter (DJF) Rainfall over the Thar Desert from 2001 to 2008 (dashed line).

over the northern parts of India is associated with VDR >0.15 (corresponding to a dust-to-total backscatter ratio of larger than 50% for a typical dust depolarization ratio of 0.2–0.3) suggesting the presence of significant amounts of dust particles as compared to that of ~20% AOD in the 2007 pre-monsoon period. Again during May, the presence of high dust contribution in 2008 is exacerbated with ~90% AOD over northern India associated with VDR >0.15, while nearly 10% optical depths correspond to moderately high VDR (ranging from 0.10 to 0.15) suggesting the contribution of local anthropogenic pollution mixed with dust.

4. Discussion

[13] In the six-year record of aerosol retrievals over bright surfaces, beginning in 2003 from the Aqua MODIS Deep Blue aerosol product, we find that the MAM07 AOD is significantly lower over the Thar Desert compared to previous individual years as well (45% drop in MAM07 AOD relative to the mean value for MAM 2003–2006) (Figure 4). The significant reduction in dust loading is also observed in the GP as suggested by the high value of angstrom exponent (0.74) during the 2007 pre-monsoon season (Figure 4) which is found to be most pronounced in May. The angstrom exponent during May 2007 is 0.78 (suggesting dominance of fine-mode particles), whereas other individual years, since 2001, are characterized by low values in the range of 0.2–0.5. In addition, the size distribution parameter, averaged during May 2001–2006, also indicates significantly higher value (coarse-mode peaking at 0.37 $\mu m^3/\mu m^2$ which is close to that of 2008) compared to the exceptionally lower value of 0.08 $\mu m^3/\mu m^2$ during 2007. Our study based on detailed characterization of aerosols and their inter-annual variations over the source region, i.e., the Thar Desert as well as over the GP, suggests an unusually weak dust-laden pre-monsoon season during 2007.

[14] What is the cause for this anomaly? One of the primary factors governing dust emissions over arid regions is the wetness of the surface which is influenced by the amount of rainfall that the region receives [*Tegen and Miller*, 1998; *Prospero et al.*, 2002]. Heavy rainfall results in the increase of soil moisture thereby reducing dust emissions over source regions. Over India, the summer monsoon rainfall (June–September) accounts for over 70% of the annual precipitation, while the winter monsoon (also known as the retreat of the southwest summer monsoon) contributes very little to the annual rainfall during December–January–February (DJF).

[15] The climatological mean winter (DJF) rainfall over the Thar Desert is very low (~7 mm) as indicated by long-term record of rainfall from 1979 to 2007 (using data from the Global Precipitation Climatology Project). However, we find that the Thar Desert received the highest rainfall in the past three decades (>2 sigma) during the winter months of December 2006 and January–February 2007, i.e., preceding the 2007 pre-monsoon dust season (Figures 4 and S2a). February 2007 is marked with an anomalous sharp increase, 44 mm (59 mm, indicated by data from the Tropical Rainfall Measuring Mission Satellite) which is nearly fourfold of the climatological mean rainfall over the Thar Desert and may have very likely negatively influenced the dust-activity during the pre-monsoon season of 2007, making it an unusually weak dusty period as observed in this study. In addition, following the anomalous winter rainfall, soil moisture over the Thar Desert is found to be maximum during the 2007 pre-monsoon season with a large value of ~73 mm compared to the lower range of values from 25 to 61 mm (mean value ~45 mm) from 2001–2008 (with the exception of 2007). Apart from rainfall and soil moisture, wind speed is another key variable that may potentially influence desert dust lifting and transport. The near surface wind speed during the 2007 pre-monsoon season over the Thar Desert is found to be often higher than other years in the 3-decade period and lies within the first-order standard deviation since 1979 (see Figure S2b) suggesting little influence on the 2007 suppressed dust activity.

[16] Our literature survey indicates that the present study is one of the first to examine the possible role of winter rainfall in influencing the immediately following dust

activity over India, especially over the northern subcontinent including the dust source region. In addition to their strong influence on aerosol optical properties, dust transport over the GP significantly affects regional air quality, therefore the relationship between winter rainfall and spring dust seasons should be further investigated for reliable model forecasting of dust emissions as well. Through the integrated approach of using MODIS, CALIPSO and ground measurements, our study highlights the synergetic characterization of mineral dust in the tropospheric aerosol burden. Due to their solar absorption effects in altering the Earth's radiation budget and potentially the hydrological cycle as well, it is thus imperative to continuously monitor dust aerosols over source and sink regions in order to better understand their spatio-temporal variability from satellite and ground observations.

[17] **Acknowledgments.** We thank the different NASA and NOAA agencies that made the data, used in this study, available. Soil Moisture data were obtained from the NOAA Climate Prediction Center through the Lamont Doherty Climate Directory webpage (http://ingrid.ldeo.columbia.edu). We wish to thank the anonymous reviewers for the constructive comments in improving an earlier version of the manuscript.

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