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Influences of winter haze on fog/low cloud over the Indo-Gangetic plains

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[1] The aerosol loading in south Asia has increased considerably because of the growing population, urbanization, and industrialization in recent years. To understand the effects of aerosols on cloud properties in this region, we have analyzed an extensive collection of aerosol and cloud properties, obtained from the Moderate resolution Imaging Spectroradiometer (MODIS) data, over the Indian subcontinent during winter 2000–2006. During these winter months, the Indo-Gangetic (IG) plains, in the northern part of India, are subjected to dense haze and fog on the basis of MODIS climatology of aerosol optical depth and cloud properties (cloud effective radius, cloud top pressure, and cloud fraction), respectively. We derive a fog/low-cloud detection scheme from MODIS level 2 data to generate distribution of fog/low cloud on a daily basis for December–January 2000–2006. Interactions between winter haze and fog/low cloud over the IG plains were analyzed by minimizing the effect of dynamical processes associated with fog formation. On the basis of the interannual variability of meteorological parameters, winter 2004–2005 was associated with favorable conditions for fog formation in terms of comparable values of relative humidity with respect to previous years. However, significantly lower fog occurrences were found in winter 2004–2005 over the IG plains from MODIS and ground observations, while higher aerosol loading was observed in 2004–2005 compared to previous years. Thus the role of higher aerosol loading in 2004–2005 was investigated, combined with the high concentration of black carbon (BC) aerosols over the IG plains, indicated by aerosol transport model, suggesting that the BC aerosols may have significant impact on the fog/low-cloud formation over the IG plains and hence less fog in winter 2004–2005.

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1. Introduction

[2] The Asian continent is the world's largest living habitat with about 60% of the world's population. Especially, south Asia has been undergoing high transformations in the urban and industry sectors, because of the growing population and globalization. India and China are the two most populated and developing nations in the world and are primarily responsible for the pollution in Asia. *Guttikunda et al.* [2003] studied the contribution of megacities to sulfur emission and pollution in Asia over a 25-year period (1975–2000) and found that Asian megacities cover <2% of the land area, but emit ~16% of the total anthropogenic sulfur emission of Asia. Percentage increase in the SO_2 emissions in India has been reported to be 47% per decade during 1979–2000 and is attributed to the increased population over the years [*Massie et al.*, 2004]. A recent study has shown that the biofuel combustion is the largest source of black carbon emissions in India, and suggests that it needs to be addressed for climate change mitigation in the south Asian region [*Venkataraman et al.*, 2005]. Other major sources of aerosols in this region are seasonal biomass-burning smoke and dust storms.

[3] Recent studies using MODIS, Multiangle Imaging Spectroradiometer (MISR) and AERONET data have shown high Aerosol Optical Depth (AOD) during winter over northern India [*R. P. Singh et al.*, 2004; *Girolamo et al.*, 2004; *Prasad et al.*, 2004; *Ramanathan and Ramana*, 2005; *Jethva et al.*, 2005]. The effect of anthropogenic aerosols on the atmospheric radiation balance has been measured over the Indian Ocean, during INDOEX, with large perturbations at the surface than at the top of the atmosphere [*Satheesh and Ramanathan*, 2000], leading to a large cooling at Earth's surface and a strong warming of the atmosphere.

[4] A more complex microphysical phenomenon involving the interactions between aerosols and clouds (the "indirect effect") has large uncertainties associated with climate forcing [*Houghton et al.*, 2001]. Their interactions cause reduction in cloud droplet size thereby, an increase in

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cloud albedo and suppression in precipitation. Studies in the past, based on in situ and short-term events, have shown the reduction in the formation of precipitation by the interaction between mineral aerosols and clouds [*Chen et al.*, 1998; *Rosenfeld et al.*, 2001; *Zuberi et al.*, 2002]. Increase in cloud cover due to the presence of aerosols leads to a further increase in the reflection of solar radiation. However, there is another mechanism that suggests reduction in cloud cover due to aerosols, particularly soot (over the northern Indian Ocean), and is thus responsible for offsetting the radiative cooling at the top of the atmosphere [*Ackerman et al.*, 2000].

[5] Despite large uncertainties in climate forcing due to the presence of various types of aerosols over the Indian subcontinent, there has not been much analysis of the aerosol-cloud interactions in this region. In this paper, we consider the relationship between aerosols and fog/low cloud over India, using remote sensing data. Fog formation usually begins in the latter half of December and continues till the end of January, thus blanketing some regions for more than a month [*Ali et al.*, 2004]. The low topography of the IG plains, adjacent to the Himalayan ranges, favors formation of fog given the high concentration of air pollutants in the plains which serve as additional CCN for nucleation. The widespread fog extends over a stretch of ~1500 km in length and ~400 km in width, with severe fog events blanketing the entire IG plains including parts of Pakistan and Bangladesh on the western and eastern sides, respectively. Fog affects day to day lives of millions of people living in this region, resulting in poor visibility down to less than 100 meters causing frequent flight and train delays and even a significant number of deaths from vehicular accidents in many severe events [*Hameed et al.*, 2000]. Also, the number of foggy days, during winter, has been increasing in recent years as compared to earlier decades [*S. Singh et al.*, 2004], with strong increasing trends of anthropogenic pollution in the IG plains [*Sarkar et al.*, 2006]. However, detailed studies of aerosol chemical composition and interannual variation of aerosols are required to better understand the interaction of the winter haze with the formation of fog over the IG plains. During winter season, major dynamical process is the northeast monsoon (driven by light winds) that brings in little rainfall over northern India. In this paper, we study the interactions between haze and fog/low cloud over the IG plains by separating other types of clouds and minimizing the role of the dynamics associated with the formation of fog.

2. Data Sets

[6] MODIS level 3 data were obtained for the period 2000–2006 from the NASA Distributed Active Archive Center (DAAC) to analyze the interannual variations and climatology of aerosol loadings and cloud properties. Globally gridded monthly mean products, with spatial resolution of 1° by 1°, of aerosol optical properties, such as AOD and Fine Mode Fraction of optical depth (FMF), were used in this study along with cloud property data sets, such as Cloud Effective Particle Radius (CEPR), Cloud Fraction (CF) and Cloud Top Pressure (CTP). The AOD is an indicator of the column loading of all sized pollutants, while FMF represents fine mode particle size fraction of the AOD. The AOD is retrieved at 550 nm from MODIS. CEPR consists of the radius of water droplets as well as ice particles present in clouds.

[7] In addition, daily level 2 data were used, with pixel resolution of AOD product of 10 km, while 5 km for CEPR and 10 km for CTP and CF data sets. The Aqua satellite was launched in 2002; therefore data for 2002 onward were obtained to study the morning-afternoon variations from both Terra and Aqua.

[8] Ground data related to meteorological observations were obtained from Russia's Weather Server–Weather Archive (http://meteo.infospace.ru/wcarch/html/index.sht). Data for 16 stations in the IG plains were available from the archive for the period December–January 2000–2006. Various meteorological parameters such as temperature, pressure, wind speed/direction, relative humidity, visibility and weather conditions (such as dust, haze, fog) were obtained from this data set. The weather conditions data were particularly useful for this study since they provide information on the number of days of fog occurrences. The weather conditions data are represented by meteorological SYNOP codes, ranging from 40 to 49 for foggy conditions, with different criteria such as "sky not visible during fog," "sky visible during fog" and so on and so forth. We filtered out the days in our analysis when sky was visible during fog events in order to have a correspondence with the satellite detected fog/low cloud. However, a direct comparison between the number of MODIS detected fog/low cloud and ground observed fog occurrences may not be appropriate because of the presence of multideck clouds and the gaps between satellite overpasses.

[9] Level 2 data for three December–January (DJ) years (2002–2003 to 2004–2005), from Terra and Aqua MODIS, were collocated over the AERONET station in IG plains (Kanpur: 26.45 N, 80.346 E) to relate fog/low-cloud variations with aerosol retrievals from AERONET results. Radiosonde data for temperature profiles and dew point temperature were obtained from http://raob.fsl.noaa.gov/ to corroborate the presence of fog. Finally, the Global Ozone Chemistry Aerosol Radiation Transport (GOCART) model [*Chin et al.*, 2000] outputs were obtained to determine the spatial distribution of black carbon aerosol optical depth over the Indian subcontinent.

3. Seasonal Variability of Aerosols Over India

[10] The northern part of India consists of the IG plains which are one of the world's largest, and highly agriculturally productive and fertile plains (Figure 1). More than one third of the total Indian population (~500 million) lives in the plains and uses various hydrological resources. The IG plains face dust storms during April-May-June (premonsoon period) [*Dey et al.*, 2004; *El-Askary et al.*, 2006]. These dust storms generally originate in the Thar Desert in India and Middle East deserts, and are transported by westerly winds in the premonsoon period. Saharan deserts have also been found to be a source of long-range transport of dust aerosols, on the basis of back trajectory analysis [*Dey et al.*, 2004]. These dust storms hit the IG plains and are not transported further since they are blocked by the high-altitude Himalayan ranges. This results in the accumulation of large amounts of dust over the IG plains.

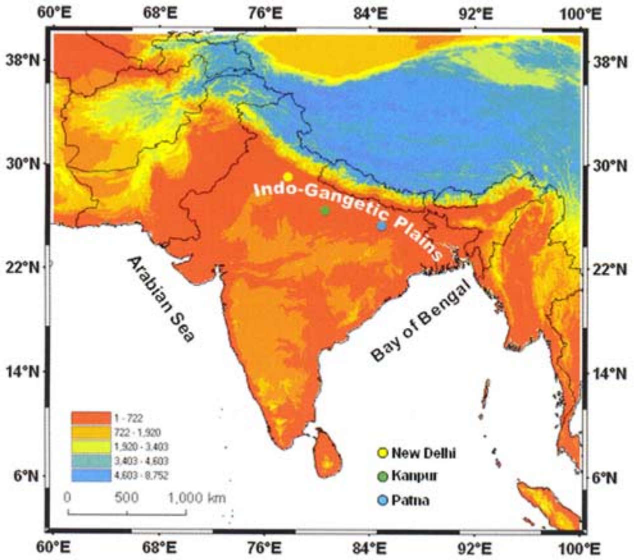

Figure 1. IG plains in the northern part of India with digital elevation model shaded. Topography data were obtained from ftp://edcftp.cr.usgs.gov/pub/data/gtopo30/.

[11] Anthropogenic emissions, in the form of BC and sulfate aerosols from biomass combustion, power plants and vehicular pollution, are present throughout the year over the IG plains [*Reddy and Venkataraman*, 2002a, 2002b]. Such aerosols form thick layers of haze in winter, recently termed as Atmospheric Brown Clouds [*Ramanathan and Crutzen*, 2003], with their large-scale effect on the entire plains. Low single scattering albedo (0.73–0.85) indicates highly absorbing aerosols in this region during winter [*R. P. Singh et al.*, 2004]. Because of the increase in aerosol concentrations, particularly BC, strong negative trends of summer monsoon rainfall, surface evaporation and surface solar radiation have been observed over the Indian subcontinent [*Ramanathan et al.*, 2005].

[12] Figure 2 shows the AOD and FMF variations, during 2001–2006, over three urban/industrial cities in the IG plains: New Delhi, Kanpur and Patna. Sulfate and BC aerosols belong to the fine mode size category, while dust particles fall in the coarse mode category. High AOD values during April–May are attributed to large dust loading in the atmosphere, while FMF shows high values during winter due to the urban/industrial and biofuel emissions.

[13] Since the present paper focuses on the interactions of aerosols with fog including low cloud, we considered individual winter (DJ) seasons to determine the spatial and temporal variations of AOD. Spatial distribution of AOD from higher-resolution level 2 data shows high aerosol loading during winter over the northern part of India, especially the IG plains, a distinct pattern not present over the rest of India (Figure 3). It is noted that year 2004–2005 indicated significantly higher AOD over the IG plains compared to other years. The implications of higher aerosol loading in DJ 2004–2005 are discussed in section 5 for studying aerosol-fog/low-cloud interactions. Comparison of AOD retrieved from MODIS and AERONET, over the IG Plains, yields good agreement during postmonsoon and winter seasons (September–March) and low agreement during premonsoon and summer monsoon period because of the abundance of westerly/southwesterly wind blown dust aerosols from the Middle Eastern, Sahara and the Thar deserts [*Tripathi et al.*, 2005]. The current MODIS aerosol retrieval algorithm uses a dark target approach with lack of retrievals over desert areas and other bright reflecting surfaces [*Kaufman et al.*, 1997; *Hsu et al.*, 2004]. Regions marked in white (Figure 3), primarily the Taklimakan and Middle Eastern deserts; show the resulting gaps in the MODIS aerosol retrievals.

4. Fog/Low Cloud Over the IG Plains

[14] During winter season, the entire northern India, especially the IG plains, suffer from western disturbances (a series of alternate low- and high-pressure systems), which move from west to east, leading to intense haze and fog in the region. A low-pressure system results in enhanced moisture content in the boundary layer, high winds and clouds, which is subsequently replaced by a high-pressure system leading to clear-sky conditions, low winds, radiative cooling of the ground, temperature inversions, and subsequently water vapor inversions [*Pasricha et al.*, 2003]. During this period, the temperature also reaches its minimum value with increased frequency of western disturbances. These conditions are ideal for accumulation of pollutants within the boundary layer and often result in fog formation over the IG plains.

[15] In an attempt to separate out and characterize fog/low cloud from other types of clouds, we computed the climatological means of CF, CEPR and CTP (Figure 4) during DJ months. Significantly higher CF is found over the IG plains indicating enhanced cloud formation during winter (Figure 4a). CEPR values over the IG plains are much lower than the precipitation threshold (i.e., 14 microns, which is used as a cutoff between precipitating and nonprecipitating clouds [*Rosenfeld and Gutman*, 1994]) and stand out well compared to the rest of the subcontinent (Figure 4b). Figure 4c shows CTP over IG plains to be ~900 mbar, suggesting cloud tops in the vicinity of ~1 km altitude. To further establish the presence of fog/low cloud, several MODIS level 2 data were analyzed. One such case of 24 December 2004 (Figure 5a) shows patch of clouds extending throughout the plains adjacent to the foothills of the Himalayas. CEPR values are less than 14 microns and the cloud tops are at an altitude of ~1.2 km (850 mbar) (Figures 5c and 5d). Radiosonde data show temperature inversion based at ~975 mbar pressure level with dew point temperature very close to the ambient temperature (Figure 5e). These observations together suggest the presence of fog/low cloud over the IG plains. It should be noted that fog observations from Terra MODIS may only represent thick fog events, since some fraction of fog is expected to burn off at the time of Terra overpass (1030 local time).

[16] In addition, comparison of the level of cloudiness in morning and afternoon, Terra and Aqua respectively, substantiates the presence of fog. Daily level 2 data for AOD and CEPR from inferred from the Terra and Aqua measurements during winter 2002–2003 to 2004–2005 were analyzed to characterize the changes in cloudiness from morning (1030 LT) to afternoon (1330 LT) overpasses,

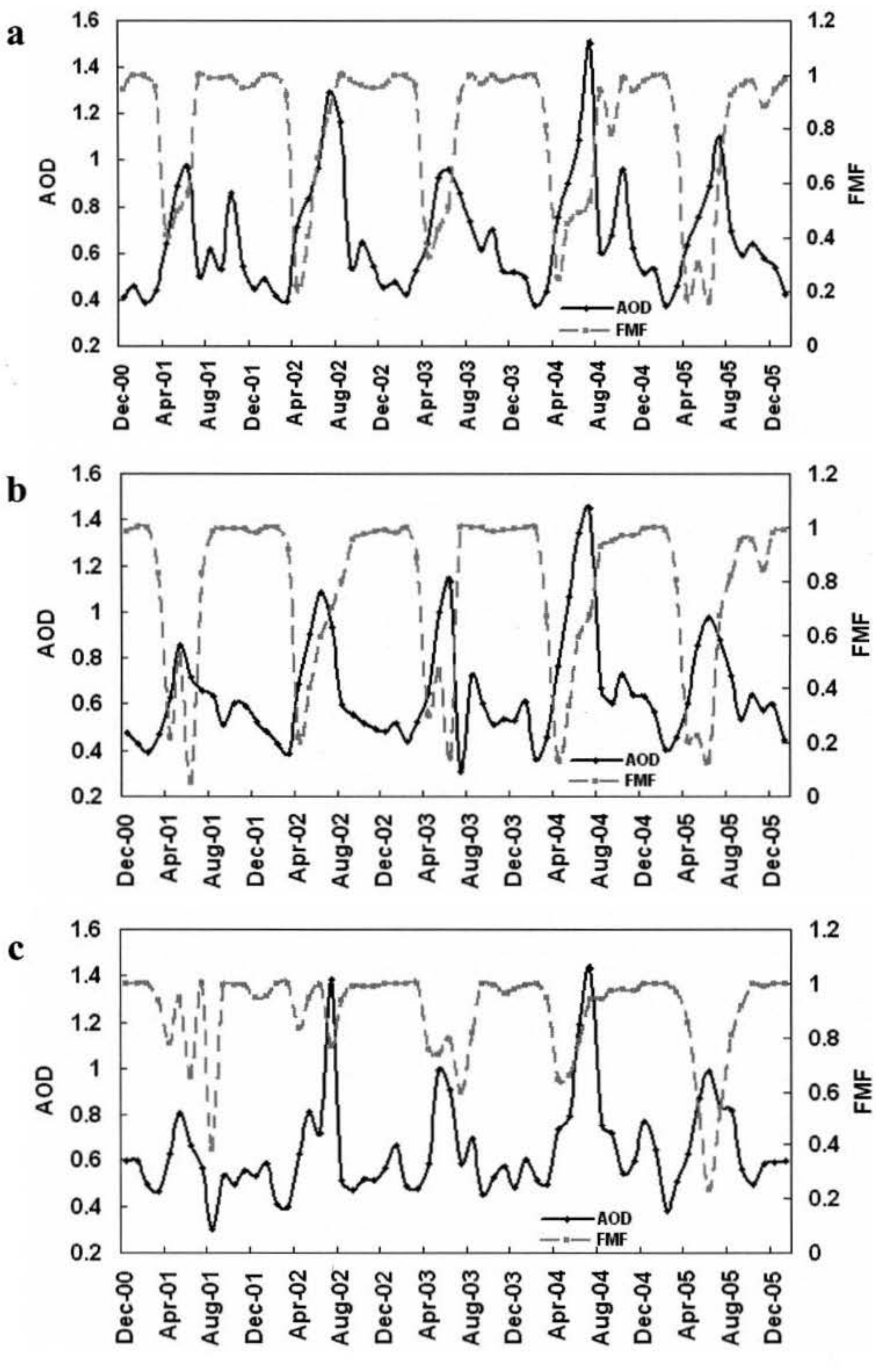

Figure 2. Variations of AOD and FMF over three cities in the IG plains: (a) New Delhi, (b) Kanpur, and (c) Patna.

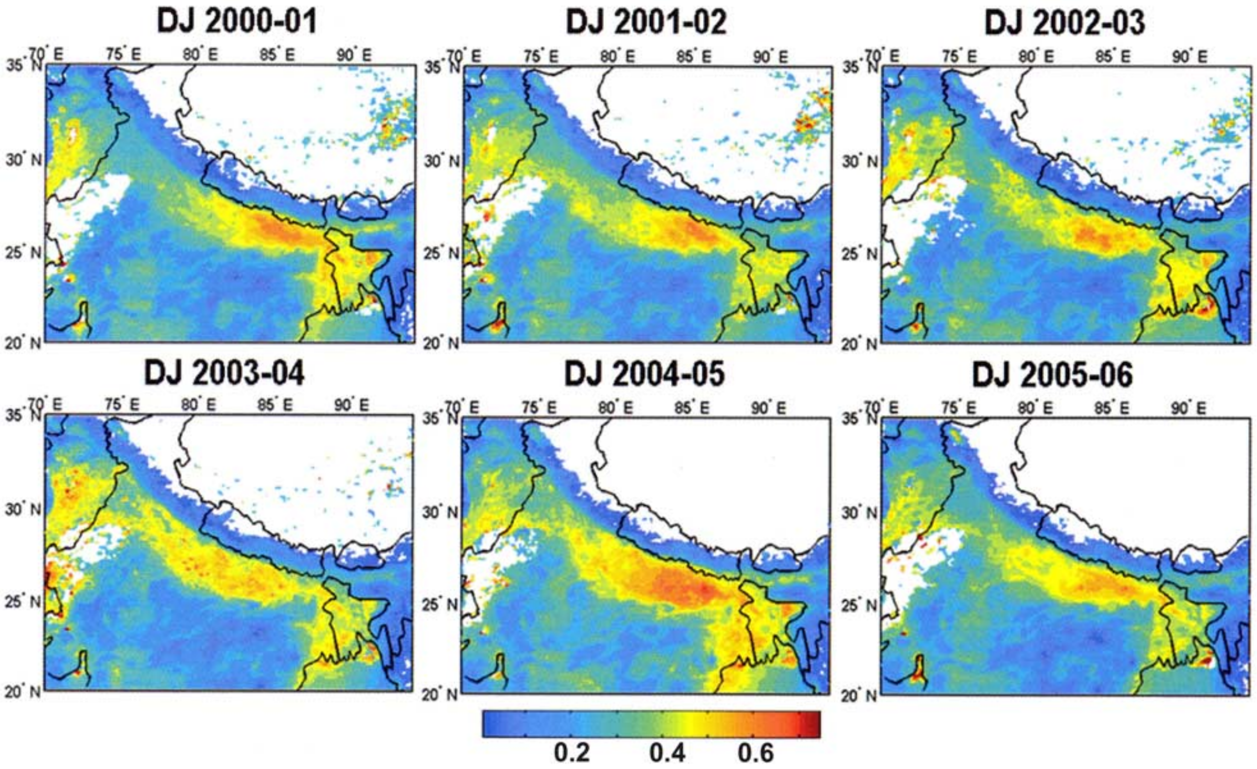

Figure 3. Year-to-year variations of AOD during winter months (DJ).

respectively. Figure 6 shows histogram plots for AOD and CEPR during winter 2002–2003 to 2004–2005 from Terra and Aqua, with number of retrievals on the *Y* axis. Because of greater fog/low-cloud formation in the morning, number of aerosol retrievals was less from Terra as compared to Aqua. Fog often burns off in the afternoon by greater solar insolation, resulting in clear-sky conditions and hence higher number of aerosol retrievals. *R. P. Singh et al.* [2004], on the basis of AERONET observations, reported higher number of aerosol retrievals over Kanpur (located at the central flank in the IG plains) in the afternoon as compared to that in the morning. Since the level of cloudiness is expected to be higher in the morning (because of foggy conditions), the number of cloud retrievals would be higher in the morning compared to those in the afternoon. Histogram plots of CEPR, from Terra and Aqua, show an out-of-phase relationship with respect to AOD: more CEPR retrievals in the morning compared to those in the afternoon. The mean value of CEPR from Terra (~8.4 μm) is also slightly greater than that from Aqua (~8.1. μm). Similarly, the number of retrievals of cloud fraction was 76 from Terra and 59 from Aqua in the November to January period from 2002–2003 to 2004–2005 (higher in morning compared to afternoon).

[17] On the basis of the distinct characteristics of cloud properties obtained from MODIS data as described above, a fog/low-cloud detection scheme was derived to distinguish fog/low cloud (Figure 5b) from high-level and precipitating clouds. Figure 7 shows the steps involved in the fog/low-cloud detection. In addition, artifacts in cloud retrievals were found in the data, such as in the presence of thick aerosol haze. In heavy aerosol loading conditions, aerosol and cloud products (MOD04 and MOD06) showed retrievals of both aerosol and cloud properties over the same pixel, respectively. The MODIS cloud mask appears to be a possible solution to deal with such artifacts, since the cloud mask classifies pixels as cloudy or clear in order to retrieve their properties. However, in the presence of thick aerosol haze (with the help of visual analysis of true color RGB images), the MODIS cloud mask for such pixels was often flagged as "undetermined." Therefore cloud retrievals over the pixels, where aerosol properties were also retrieved, were filtered out. Another type of cloud misretrieval was encountered over the Thar Desert (western India): MODIS cloud products showing retrievals of cloud properties over desert regions in the clear-sky or cloud-free conditions. CTP over the desert regions were invariably ~1000 mbar in clear-sky conditions for all level 2 data during December–January. These artifacts were identified during the analysis and filtered out. In order to separate fog/low-level clouds from high clouds, pixels having CTPs lower than 780 mbar were filtered out. Also, high precipitation efficiency clouds, with CEPR values greater than 14 microns, were ignored. In essence, this scheme generates distribution of fog and clouds with their tops below ~2.1 km. These steps were very important in dealing with aerosol-fog/low-cloud interactions and subsequently strengthened our analysis and conclusions.

5. Aerosol and Fog/Low-Cloud Interactions

[18] In this study, our primary goal is to study aerosol-fog/low-cloud interactions over the IG plains in winter by minimizing the role of dynamics associated with fog for-

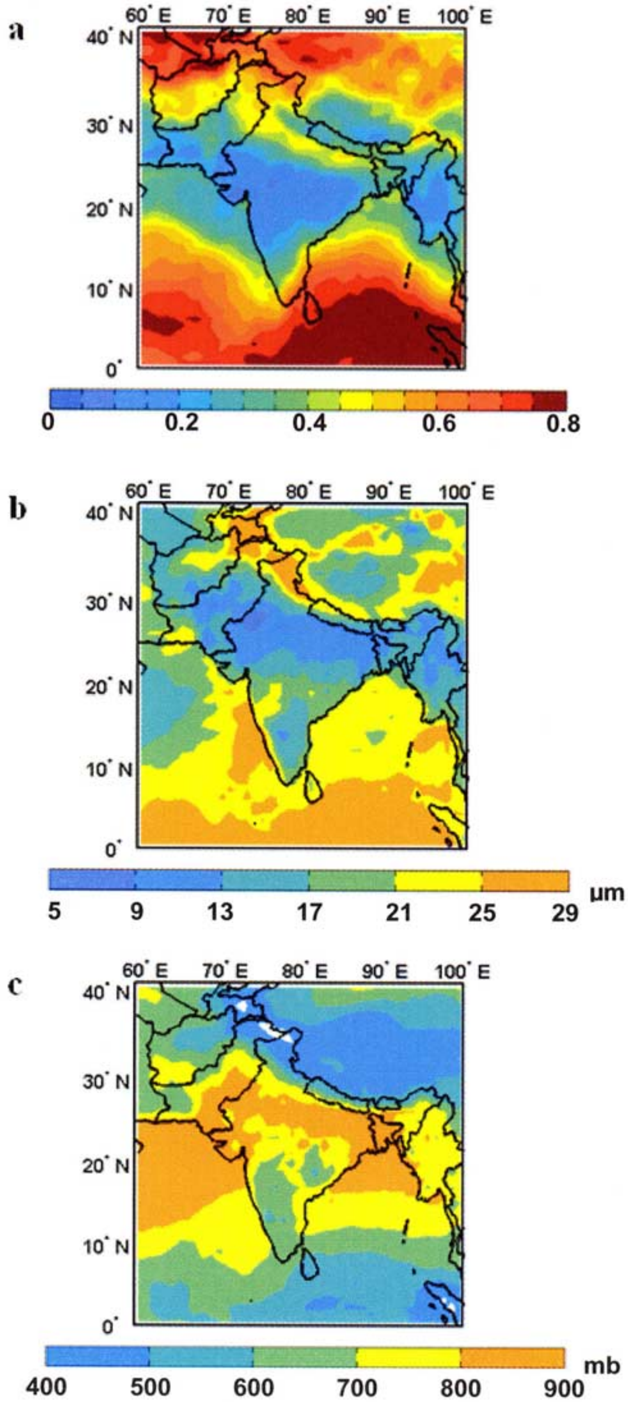

Figure 4. Winter climatology of (a) CF, (b) CEPR, and (c) CTP suggesting the presence of fog/low cloud over the IG plains.

mation. Meteorological variables from NCEP data such as moisture, surface temperature/pressure and wind fields for the period 2000–2005 are shown in Figure 8. Dry northeast monsoon (with little rainfall over northern India) prevails during winter, where calm winds blow off the subcontinent. However, because of the coarse resolution of the NCEP data (1.8° by 1.8°), meteorological variables from surface observations were also analyzed to better understand their interannual variations. Figure 9 shows the interannual variations of relative humidity (RH) over selected locations in the IG plains from surface observations. These locations are arranged in a longitudinal fashion from west to east in Figure 9.

[19] In order to study the interactions between aerosols and fog/low cloud over the IG plains, we selected the period 2001–2005 where the values of RH are comparable in all four years. The monthly mean RH values for the period DJ 2001–2005 are within 75–80% over the IG plains. In addition, little interannual variation in aerosol loading is found during DJ 2001–2004, while significantly higher AOD is found over the IG plains in DJ 2004–2005 (Figure 3). Thus, to infer any significant influences of aerosols on fog/low cloud over the IG plains, we generated composite maps of fog/low-cloud frequency (number of days of fog/low-cloud occurrences) from MOD04 and MOD06 granules for the period DJ 2001–2005, following the methodology of deriving fog/low-cloud distribution. Figure 10 shows the fog/low-cloud occurrences map for DJ 2001–2004 and DJ 2004–2005. The spatial distribution suggests significantly lower fog/low-cloud occurrences in DJ 2004–2005 compared to DJ 2001–2004 with maximum number of fog/low-cloud occurrences as 22 and 15 days in the IG plains for DJ 2001–2004 and 2004–2005, respectively. It should be noted here that the Terra MODIS data were unavailable for a 10 days period from 16–25 December 2003 and henceforth, the mean fog/low-cloud occurrences in DJ 2001–2004 (Figure 10a) are possibly short of a few number of days. In addition to the MODIS detected fog/low cloud, we also show a composite map of fog occurrences in DJ 2004–2005 from surface observations that indicate 14 days as the maximum number of foggy days (Figure 10b, bottom plot). The ground data includes only the days when sky was obscured during fog events, on the basis of the SYNOP codes described in section 2. Similar spatial pattern of fog occurrences from surface observations and fog/low-cloud occurrences from Terra MODIS (Figure 10) suggest that the MODIS detected low cloud may actually be fog with their base close to surface. These observations together suggest that the dynamical processes alone may not explain the lower fog/low-cloud formation in winter 2004–2005.

[20] To understand the cause of the lower fog/low-cloud occurrences, we carried out further investigations by exploring what appears to be significantly higher black carbon concentrations in the IG plains, indicated by GOCART model outputs (Figure 11) as well as by emissions inventory from biomass combustion [*Reddy and Venkataraman*, 2002b]. Recent studies also attribute high pollution over the IG plains to the dense network of coal based power plants, which significantly affect BC concentrations [*Prasad et al.*, 2006]. Pure BC particles belong to the hydrophobic species of aerosols and acquire hydrophilic coating, as they age in the atmosphere. As BC becomes sufficiently hydrophilic, it serves as CCN for cloud formation. However, these BC particles (part of the CCN population) effectively absorb solar radiation and further release the absorbed heat, thereby increasing the critical supersaturation of the CCN. This prevents the activation of CCN and further reduces the ability of the CCN population in becoming cloud droplets [*Conant et al.*, 2002].

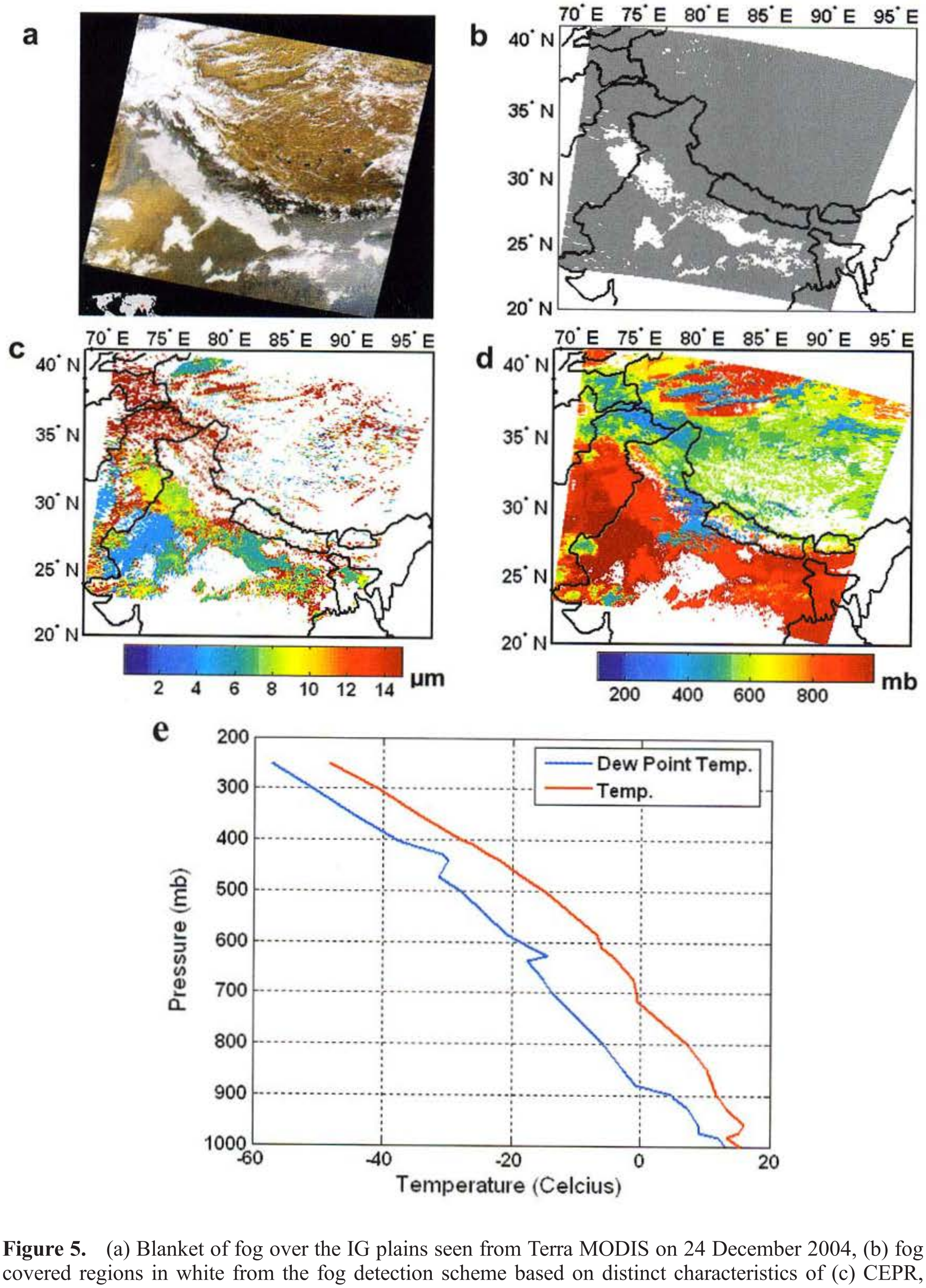

Figure 5. (a) Blanket of fog over the IG plains seen from Terra MODIS on 24 December 2004, (b) fog covered regions in white from the fog detection scheme based on distinct characteristics of (c) CEPR, (d) CTP, and (e) radiosonde data showing temperature inversion in the layer of ~975 mbar.

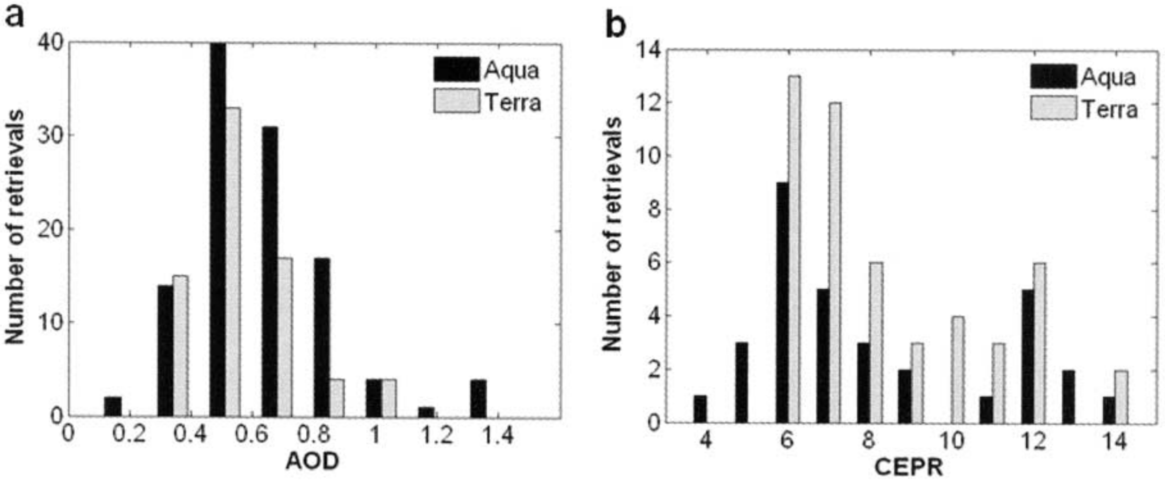

Figure 6. Morning (1030 LT) and afternoon (1330 LT) histograms from Terra and Aqua over Kanpur for (a) AOD and (b) CEPR.

[21] Thus the higher aerosol loading in winter 2004–2005 over the IG plains compared to other years, combined with the high concentrations of BC aerosols, may act to suppress cloud formation, resulting in lower fog/low-cloud occurrences. Satellite based inferences and modeling studies have shown the role of BC or soot on the suppression of the fraction of cumulus/stratocumulus clouds [*Ackerman et al.*, 2000; *Koren et al.*, 2004]. Our results, presented in this study, are related to different category of clouds, i.e., fog/low cloud over IG plains, however inferred from similar mechanism where BC aerosols cause reduction of fractional cloudiness. It is also possible that aerosols and cloud formation can be independent of each other and hence not following in sequence. However, as shown earlier, here we have carefully chosen the winter years to minimize the effect of dynamics and focus on the role of aerosols, as one of the important factors, causing reduction of fog in 2004–2005. The present work and results inferred are based on satellite observations, however, to fully understand the complex interactions between haze particles and fog, in situ observations of the chemical composition of aerosols and

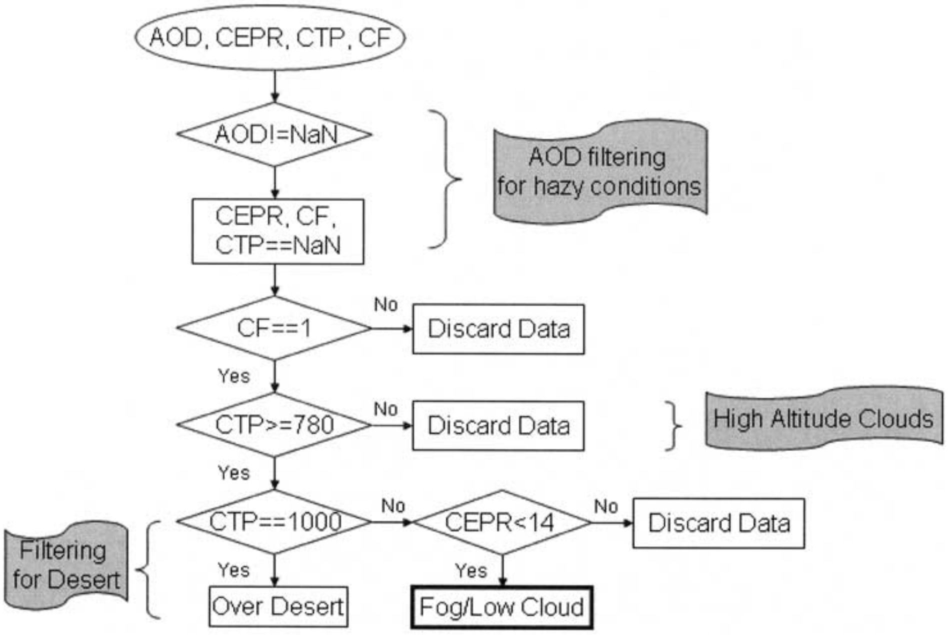

Figure 7. Flow diagram of the fog detection scheme derived from MODIS level 2 aerosol and cloud products.

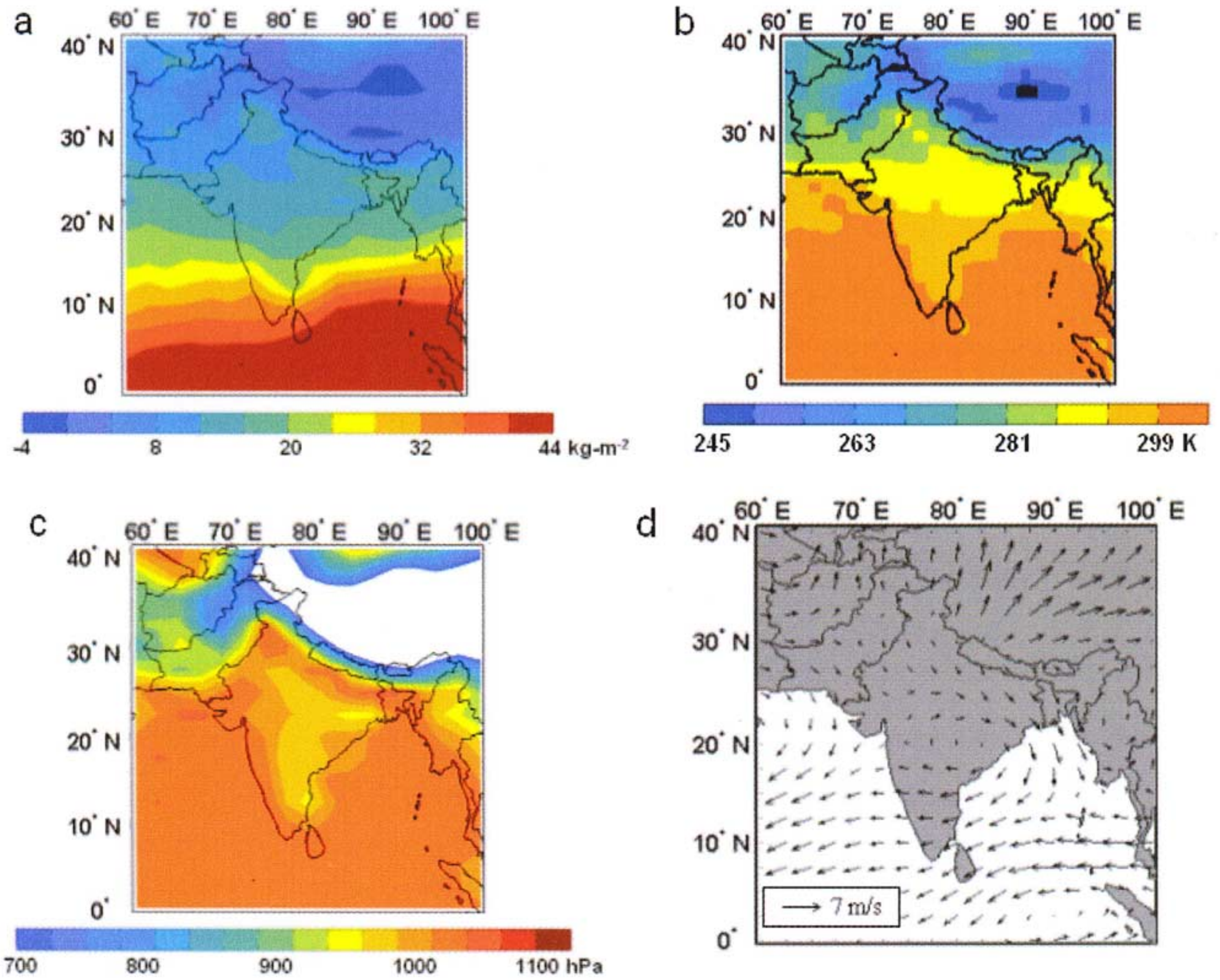

Figure 8. Winter climatology of (a) water vapor, (b) surface temperature, (c) surface pressure, and (d) wind vectors at 850 mbar pressure level from NCEP reanalysis data.

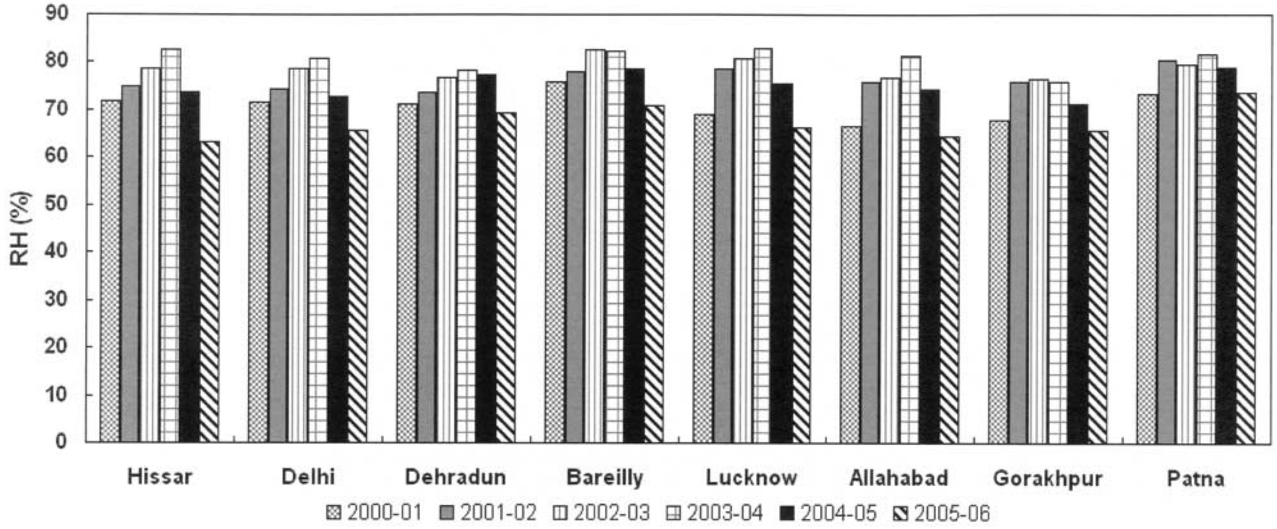

Figure 9. Interannual variations of RH during winter 2000–2006 over cities in IG plains.

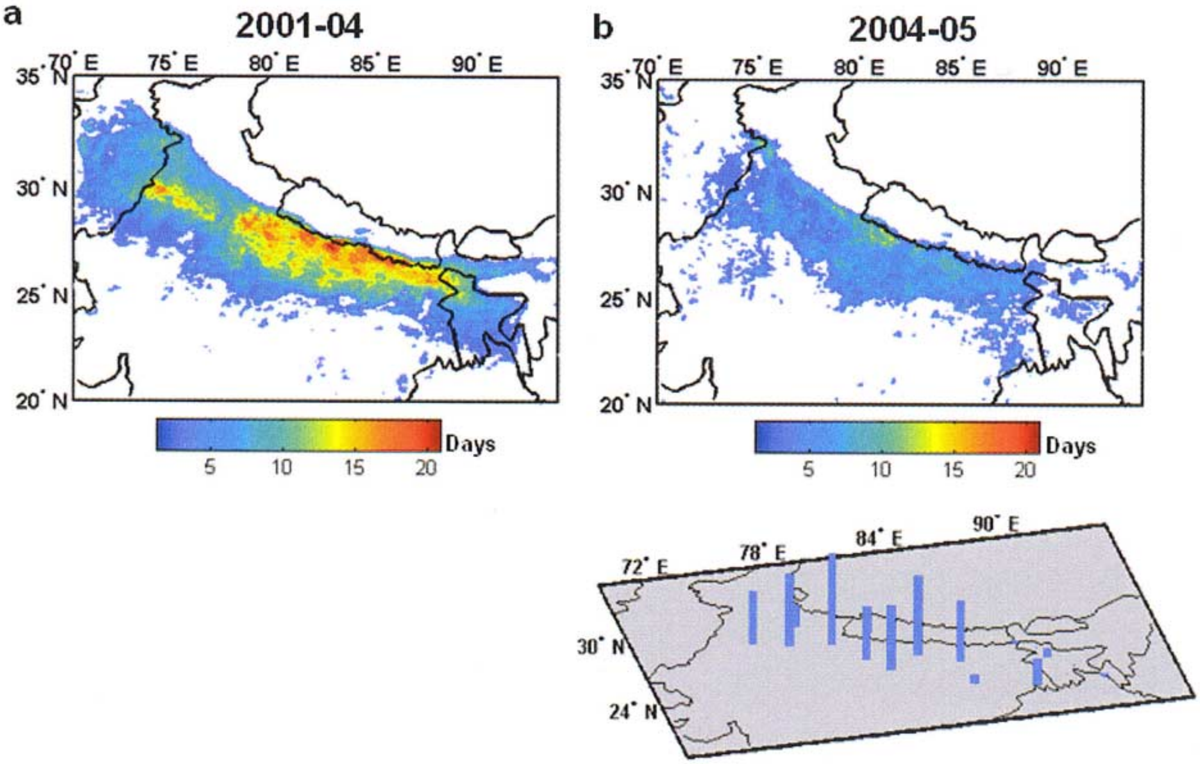

Figure 10. (a) Composite of fog/low-cloud frequency (number of fog occurrences) distribution in winter 2001–2004 and (b) 2004–2005 from daily Terra MODIS level 2 data sets following the fog detection scheme. Bottom plot in Figure 10b shows fog occurrences in winter 2004–2005 from surface observations.

microphysical properties of clouds over the IG plains are required.

6. Conclusions

[22] Higher AOD persists in northern India (in the IG plains), a distinct pattern not present in the rest of India with dust aerosols dominating premonsoon and summer seasons, while urban/industrial emissions prevailing in the winter months. Fine mode aerosols constitute the majority of the haze during winter months and are found to be significantly coupled to the widespread fog formation over the IG plains. Fog/low-cloud occurrences distribution over the IG plains was generated for winter 2000–2005, by separating high-level and precipitating clouds, using various cloud properties obtained from MODIS data. Surface observations, during winter, were also used to map fog occurrences over the IG plains, complementing MODIS detected fog/low-cloud distribution. Fog/low-cloud occurrences in winter 2004–2005 were significantly less compared to previous years with favorable meteorological conditions for the formation. Such changes in fog/low-cloud formation are most likely attributed to the higher aerosol loading in DJ 2004–2005, combined with excess black carbon concentrations due to high population density, biomass combustion and coal-based power plants over the IG plains. Since India ranks among the leading nations of emissions (with the industrialization likely to grow in the future), role of pollution particles on fog/low-cloud formation should be given serious consideration and be further investigated in terms of direct and indirect effects of aerosols, as well as with detailed studies of their composition.

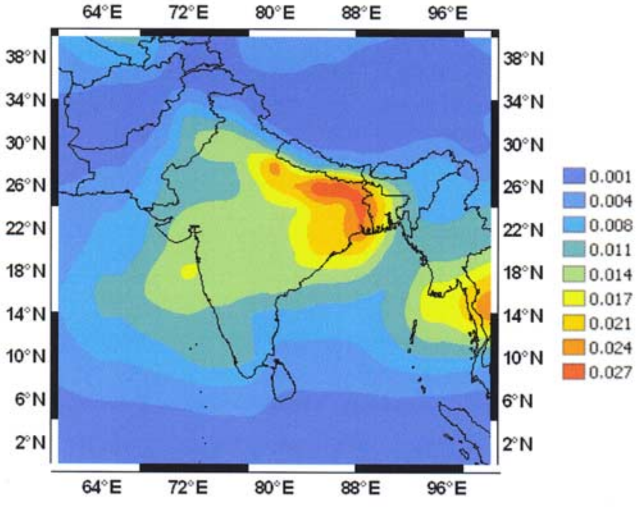

Figure 11. Black carbon AOD from GOCART model outputs during winter, showing high mass concentrations in the IG plains.

[23] **Acknowledgments.** We are grateful to the anonymous reviewers for providing constructive comments which helped to improve the manuscript. MODIS data were obtained from the NASA Goddard Distributed Active Archive Center, and GOCART model outputs were downloaded from Giovanni MODIS Online Visualization and Analysis System.

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