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Wintertime aerosol characteristics at a north Indian site Kharagpur in the Indo-Gangetic plains located at the outflow region into Bay of Bengal

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[1] Keeping the importance of aerosol characterization in the out flow regions from the Indian subcontinent in view, a campaign mode observation on aerosol physical properties was made at Indian Institute of Technology campus, Kharagpur located under the vent region in the Indo-Gangetic plains during the winter month of December 2004. The aerosol spectral optical depths and near-surface mass concentrations were high with a mean aerosol optical depth of 0.7 at 500 nm and a percent share of fine mode particle concentration as high as 90. However, the share of the BC aerosol to fine mode aerosol was consistently 10%, which is typical of an urban location. The vertical profiles of aerosol backscatter intensity derived using a micropulse lidar show that the boundary layer height variation accounts for the day-to-day variability in the surface mass concentrations. The negative correlation between aerosol backscatter intensity at two representative altitudes above and below the boundary layer implicates only vertical redistribution of aerosols. The lidar data also suggest that no aerosol transport has taken place over the location to account for the day-to-day variability. The forward trajectories at three representative altitudes with source point at the observing site indicate a possible aerosol transport from the outflow regions into Bay of Bengal, southern peninsular India and Arabian Sea. The results were discussed in light of the earlier mobile campaign observations on the spatial variability of aerosol physical properties over the peninsular India.

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1. Introduction

[2] To understand the mechanisms which define the optical state of the atmosphere, knowledge of aerosol characteristics, their spatial/temporal variability, and their interaction with other atmospheric processes/parameters is important [*Smirnov et al.*, 2002b] Aerosols are not uniformly distributed over the globe and their radiative forcing is strongly dependant on the geographical location on the earth [*Meywerk and Ramanathan*, 1999]. Though on a global scale, natural sources of aerosol dominate the man-made aerosol, regionally this factor can change significantly. Downwind of the source regions, the anthropogenic sources can be a major contributor [*Ramachandran and Jayaraman*, 2002].

[3] The discovery during Indian Ocean Experiment (INDOEX) of the so-called south Asian haze extending over south, southeast, and east Asia, during winter monsoon season has opened a new dimension to aerosol research namely the area of atmospheric haze, which is a brownish layer of pollutants and particles in many regions of Asia, that includes the Indian subcontinent [*United Nations Environment Programme and Center for Clouds, Chemistry and Climate* (UNEP and C^4), 2002]. Satellite-derived aerosol optical depth images indicate regions of high aerosol optical depth (AOD) during this season in the northern India covering the whole Indo-Gangetic plains. The haze consists of aerosols and particulate matter that have both direct effects like the reduction in the surface solar irradiance, which are restricted to regions beneath the haze layer and indirect effects that include cooling of land surface, increase in frequency and strength of thermal inversion that can trap more pollution, reduction in wintertime average rainfall patterns, reduction in evaporation, etc. [*UNEP and C*^{4}, 2002]. *Markowicz et al.* [2002] reported an observational proof for the large role of absorbing aerosol in the Mediterranean also, which is nearly identical to the highly absorbing south Asian haze observed over the Arabian Sea.

[4] Indian subcontinent and surrounding regions are rich sources for many kinds of aerosols of natural and anthropogenic origin such as mineral dust, soot, nitrates, sulfates

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and organic aerosols. This region has been the focus of investigations due to its potential impact on regional and global climate. From measurements on aerosol physical and optical properties on the Indo-Asian Haze, *Franke et al.* [2003] reported that because of the high extinction values observed in the region, it has a strong impact on regional climate. Since the particles in part were highly absorbing, possibly hydrophobic and were often found above the boundary layer, they could be transported over thousands of kilometers with out significant removal and that their impact could be much more complex. One of the best times to investigate the aerosol forcing over the Indian Ocean is during winter monsoon season when low-level transport of highly polluted air from India to the Arabian Sea and adjacent Indian Ocean can be observed [*Meywerk and Ramanathan*, 1999]. *Rasch et al.* [2001] reported that three points of entry are found for the anthropogenic aerosol to the INDOEX region; a strong near-surface southward flow near Mumbai, a deeper plume flowing south and east off Kolkata coast and a westward flow originating from south east Asia and entering Bay of Bengal. The analysis suggests that India is the dominant source of aerosol in the Arabian Sea and Bay of Bengal near the surface, but Asia, Africa and rest of the world also contribute at higher levels.

[5] During the wintertime NE monsoon (December–April) period, the prevailing low-level wind flow is from the polluted land in the north to the ocean in the south. The air mass is influenced by the uptake of gaseous pollutants and continental aerosols from the north Indian polluted region and mixes with the relatively pristine air over the oceans. *Eck et al.* [2001] reported an interannual variability in column integrated optical properties over Maldives during NE monsoon for 1998–2000, associated not only with anthropogenic plumes, but also as a result of dust transport from arid and semi arid regions. From their observations during INDOEX, *Kamra et al.* [2003] reported that there are strong indications that the nucleation mode particles found in the free troposphere by the gas to particle conversion processes in the outflow regions of clouds of the convective cells are transported down the marine boundary layer in the descending leg of Hadley cell in the northern hemisphere and then advected southward along with the continental aerosols with the persistent northeasterly surface winds in this season.

[6] The oceanic regions adjacent to the Indian subcontinent are influenced by two contrasting air mass (continental and marine) associated with Indian monsoon system. Indian summer monsoon usually starts by the end of May and continues till November. During this period, winds are mainly southwesterly westerly. The winter monsoon becomes established toward the end of November and continues till April. During this period, prevailing winds are mostly calm and north easterly. The eastern Indian Ocean is influenced by the transport from the Indian subcontinent and Southeast Asia, particularly from Indonesia. Transport of aerosols originating at three different source regions namely Arabia, the Indian subcontinent and Southeast Asia penetrate deep into the ocean areas mainly between the surface and the midtroposphere.

[7] Air of Indian origin contributes most strongly to both Arabian Sea and Bay of Bengal (BOB) regions, but the Asian plume entering the domain about 5–10°N, 100°E also plays an important role. Of the two outflow regions, the air originating over Kolkata and Bangladesh is much deeper (2.5 m thick) and extends south and east over BOB where it often merges with the Asian plume and moves south and west. The dominant contributor to AOD is the carbonaceous aerosol (about 36%), followed by dust (31%) and sulfate (26%) [*Rasch et al.*, 2001].

[8] With this background in view, and keeping the importance of characterizing the aerosol parameters in the outflow regions from the Indian subcontinent, the Indian Space Research Organization under the Indian Space Research organization (ISRO)-Geosphere-Biosphere programme organized a campaign mode observational programme at eight fixed locations in north India covering the whole Indo-Gangetic plains. The research group of Andhra University made comprehensive measurements of the aerosol physical properties at Kharagpur (22.31°N, 87.31°E, 230 m above mean sea level) located just at the mouth of the pollution outflow vent from the north Indian region into the Bay of Bengal. The measurements were made at the Regional Remote Sensing Service Centre (RRSSC) of ISRO located on the Indian Institute of Technology campus, Kharagpur.

2. Instrumentation and Data

[9] The campaign was conducted during the whole month of December 2004. The measurements included the (1) aerosol spectral optical depth at 5 wavelengths centered about 380, 440, 500, 675 and 870 nm using a Microtops Sun Photometer (Solar Light Co, United States), with a Global Positioning System (GPS) receiver attached with the Photometer to provide information on the location, altitude and pressure, (2) near-surface aerosol mass concentrations using a 10 channel Quartz Crystal Microbalance (QCM) Impactor (California Measurements Inc., United States), whose 50% aerodynamic cutoff diameters are 25, 12.5, 6.4, 3.2, 1.6, 0.8, 0.4, 0.2, 0.1, and 0.05 μm, respectively, with an air inlet at a flow rate of 0.24 L min^{-1} and sampled for duration of 120 s, and (3) vertical profiles of aerosol backscatter intensity using a SESI Micro Pulse Lidar (MPL) system, which employs an optical transceiver that acts as both transmitter and receiver (telescope) consisting of a pulsating Nd:YAG/Nd:YLF laser, Si-APD photon counting detector, signal processing unit and data processor (multichannel scalar). The wavelength used for the measurement is 532 nm green light which is the second harmonic of laser's fundamental wavelength of 1064 nm. The laser pulse duration was 100 ns, which gives a vertical resolution of 30 m. A small solid angle of the scattered light in the field view of the transceiver is received and counted by the MCS electronics as a time-gated signal. A near real time mass concentration of BC was measured using an Aethalometer (Magee Scientific, United States) by the research group of Space Physics Laboratory, Vikram Sarabhai Space Centre. The instrument which aspirates ambient air through an inlet tube connected to pump and the particles impact on a quartz filter tape, resulting in a change in transmittance of which after each collection interval is calibrated in terms of the mass of BC. The observations were started on 2 December at Kharagpur and were continued till 27 December 2004. The time resolution of AOD measurements was every half

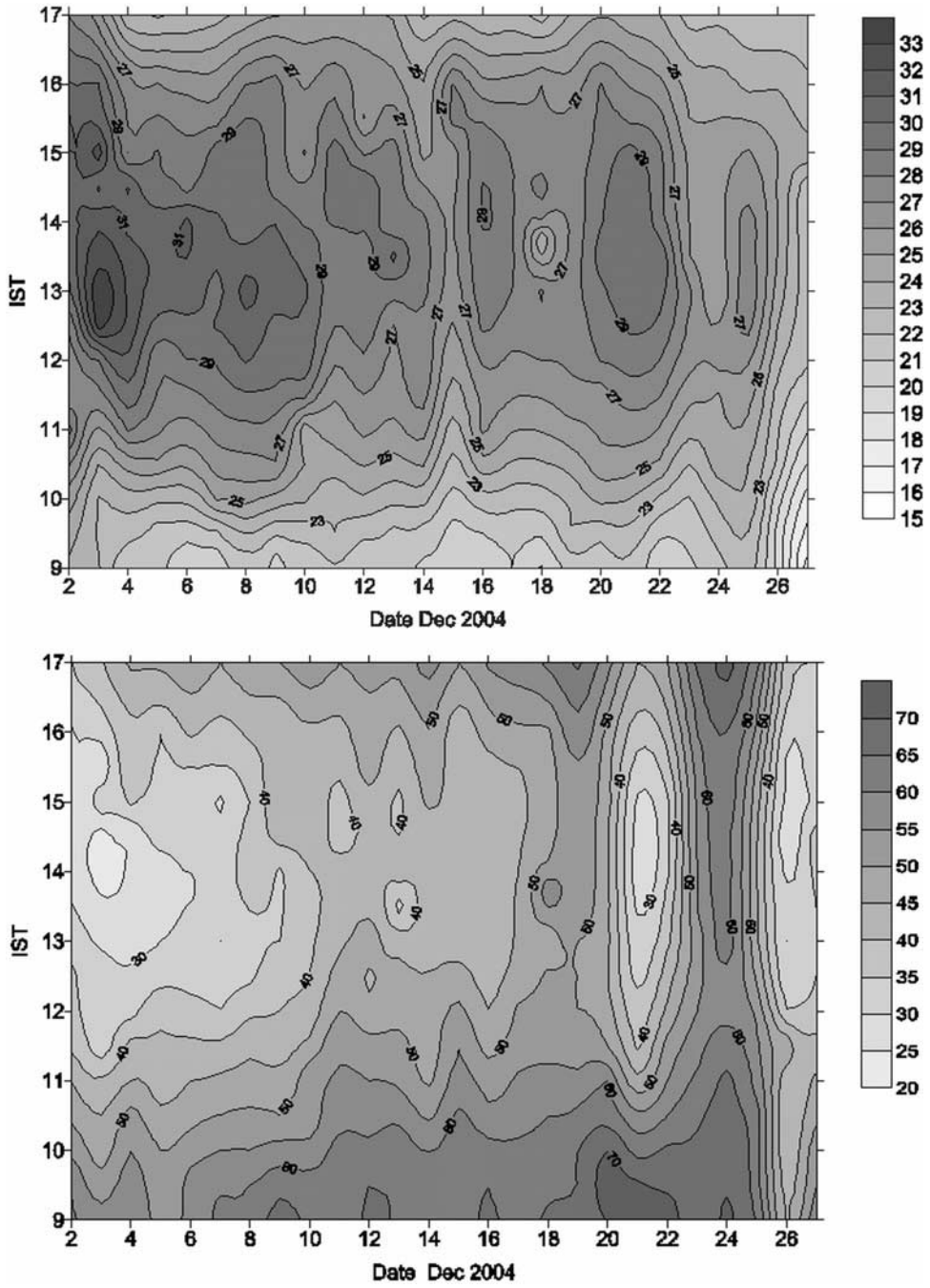

Figure 1. Contours of (top) temperature and (bottom) atmospheric humidity at Kharagpur during December 2004.

hour and the QCM system was 1 hour, Aethalometer at a time base of 5 min, round the clock. The MPL was operated every evening from 1700 to 2000 LT.

3. Prevailing Meteorology

[10] Figure 1 shows the contours of surface temperature (Figure 1, top) and relative humidity (Figure 1, bottom) as a function of day in December and time (in Indian Standard Time, LT), respectively. The surface temperature varied between a minimum of 20°C on 27 December 2004 and a maximum of 29°C on 2 December 2004. However, the daytime temperature was mostly around 25°C around 1100 LT and the surface humidity was between 40 and 50%. The range of variability of surface humidity was from a minimum of 40% to a maximum of 60%. It may be said that by and large the weather was cool and dry. As the days progressed from the start of the observations on 2 December the temperature gradually decreased and there was a slight increase in the surface humidity from 40% to 60%. The diurnal variability of temperature was about 16°C with day minimum usually occurring at 0530 LT and day maximum occurring around 1300 LT. The range of diurnal variability in surface humidity was by about 45% with day minimum

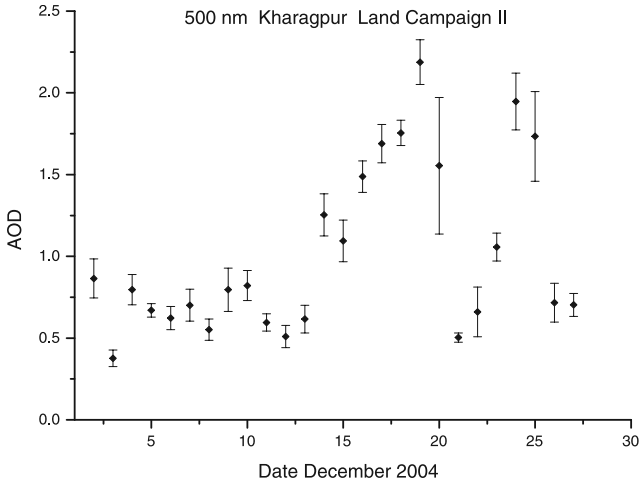

Figure 2. Daily mean aerosol optical depth (AOD) at 500 nm with standard deviation during December 2004.

occurring around 1300 LT and day maximum occurring around 0500 LT. However, the daytime temperatures were more or less constant with variability of about 8–10°C from morning to afternoon hours.

4. Aerosol Spectral Optical Depth

[11] The simplest and in principle the most accurate and easy to measure ground-based monitoring aerosol parameter is the optical depth which is the single most comprehensive variable to remotely assess the aerosol burden in the atmosphere from ground-based measurements. Figure 2 shows the day-to-day variability of daily mean aerosol optical depth at 500 nm with standard deviation shown as error bar. The AOD at 500 nm was mostly around 0.7 on all clear days. Hazy days between 15 and 25 May showed AOD of more than 1.0 at 500 nm. Figure 3 shows the contour map of 500 nm AOD as a function of time and day which shows a mean AOD of 0.7 on all clear days which is to be considered as high. Though the sky was hazy during the later part of the month, we could make AOD measurements as the sun was visible through the haze. It may also

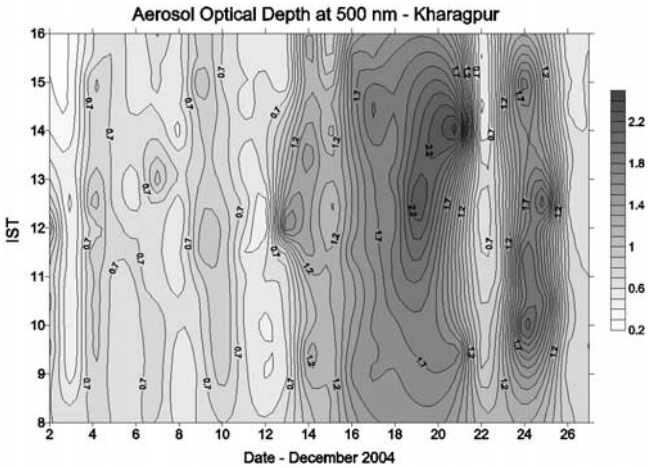

Figure 3. Contours of aerosol optical depth at 500 nm as a function of date (December 2004) and time (IST) for December 2004 at Kharagpur.

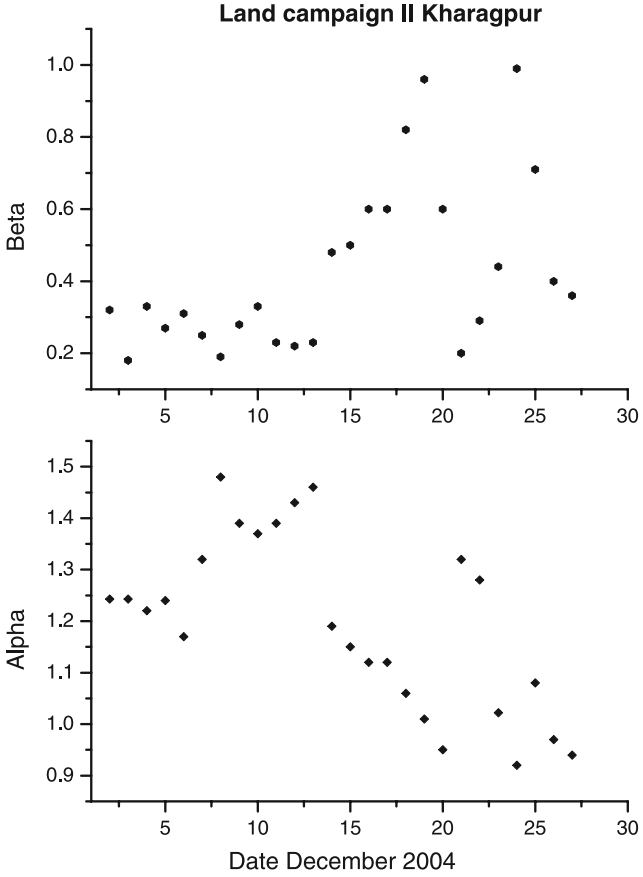

Figure 4. Day-to-day variation in Ångström parameters (top) turbidity coefficient "β" and (bottom) size index "α" at 1100 LT during December 2004.

be mentioned that during 90% of the observation period, the sky was cloud free. Further, the AODs are analyzed by fitting the Angstrom power law which is of the form $\tau = \beta\lambda^{-\alpha}$, where α is the wavelength exponent indicating the size distribution, β is the turbidity parameter which is a measure of aerosol loading, and λ is the wavelength in microns. Figure 4 shows the Ångström parameters (α and β) for all the days of observation. The α was high during the clear-sky conditions from 2 to 15 December indicating the dominance of fine mode particles while it slightly decreased during the later part of the month, when there was an increase in humidity up to 60%. The α values were never less than 0.9 indicating the anthropogenic nature of the aerosol system over the site. The light scattering of aerosol is strongly dependent on the RH at which it was measured since the ambient aerosol size distribution significantly responds to changes in atmospheric humidity. The turbidity coefficient "β" was low during the first part of the month characterized by the clear-sky condition indicating a good aerosol ventilation while the large values of β were observed during the later part of the month showing increased levels of aerosol columnar content.

5. Near-Surface Aerosol Mass Concentration

[12] Near-surface aerosol characteristics are largely dependent on the boundary layer dynamics besides on the

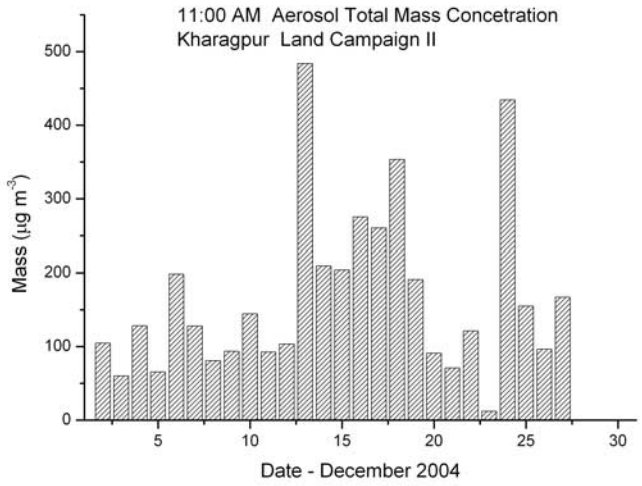

Figure 5. Day-to-day variation in near-surface aerosol total mass concentration at 1100 LT measured using the Quartz Crystal Microbalance (QCM) System at Kharagpur during December 2004.

local sources, sinks and the surface meteorology. Figure 5 shows the day-to-day variability in the near-surface aerosol total mass concentration in the size ranges 0.05 to 25 μm at 1100 hours as measured by the QCM system. It may be seen that the aerosol mass was high between 100 μg m^{-3} during clear-sky conditions and during the hazy period in the second half of the month it went to a mean of about 200 μg m^{-3}. There were two typical days, i.e., 13 and 24 December 2004, when the near-surface mass concentration was more than 400 μg m^{-3}. Figure 6 shows the variation of the atmospheric boundary layer height derived from the micropulse lidar data between 1800 and 1900 LT at the observation site. During the early part of the observation period, i.e., up to 13 December 2004, the atmospheric boundary layer (ABL) height was between 600 and 700 m, while in the later part of the month, it came down to below 400 m. This indicates that the boundary layer

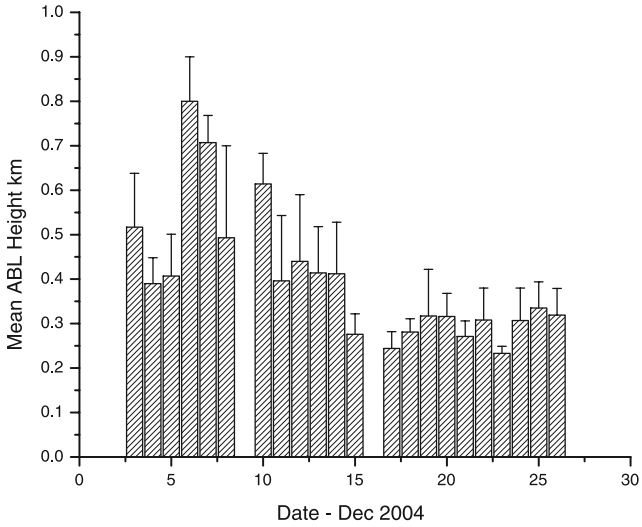

Figure 6. Day-to-day variability in the boundary layer height derived from the micropulse lidar at 1730 LT during December 2004.

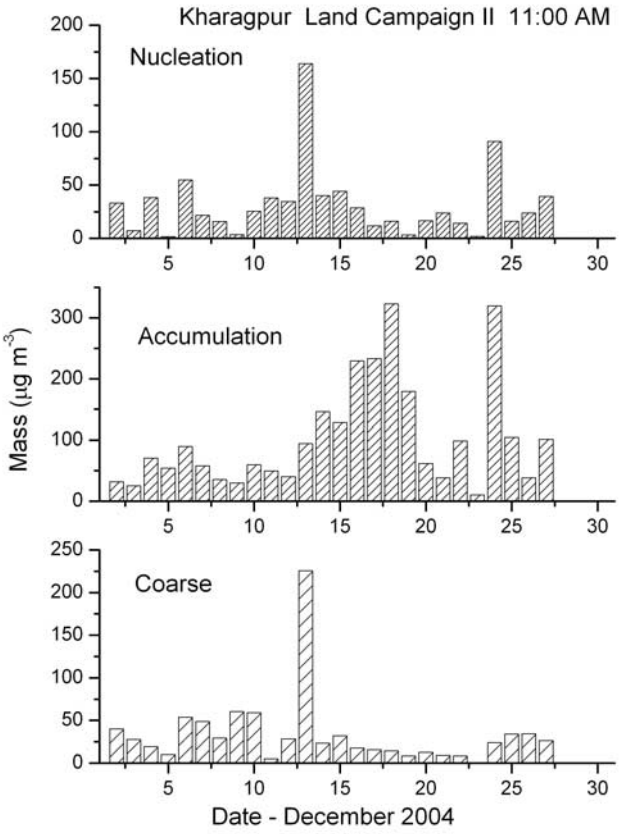

Figure 7. Size-segregated aerosol mass concentration in the nucleation (aerodynamic diameter <0.1 μm), accumulation (aerodynamic diameter between 0.1 μm and 1.0 μm), and coarse mode (aerodynamic diameter >1 μm).

dynamics accounts for the day-to-day variability in the near-surface mass concentration. A 40 to 50% compression in the boundary layer has resulted in a proportionate increase in the near-surface mass concentration from 100 to 200 μg m^{-3}. Figure 7 shows the size classified mass distribution in the nucleation (aerodynamic diameter <0.1 μm), accumulation (aerodynamic diameter between 0.1 and 1.0 μm) and coarse mode (aerodynamic diameter >1 μm). It may be noticed that the day-to-day variability is nicely reproduced in the accumulation mode aerosol while the nucleation and coarse mode aerosols do not show the day-to-day variability. However, the very high mass concentration recorded on the two odd days was reflected in the nucleation mode and coarse mode on 13 December and only in the accumulation mode on 24 December.

[13] Since aerosols are regionally concentrated, among the various species that constitute the composite atmospheric aerosols, the black carbon (BC) is the principal light absorbing constituent, which offsets partly and at times even reverses the well known white house effect due to aerosol scattering. In spite of being mostly of anthropogenic origin and a by-product of all combustion activities, the black carbon heating of the boundary layer can strengthen the low-level inversion which can in turn perturb low-level clouds, enhance aerosol lifetimes and alter the boundary layer moisture.

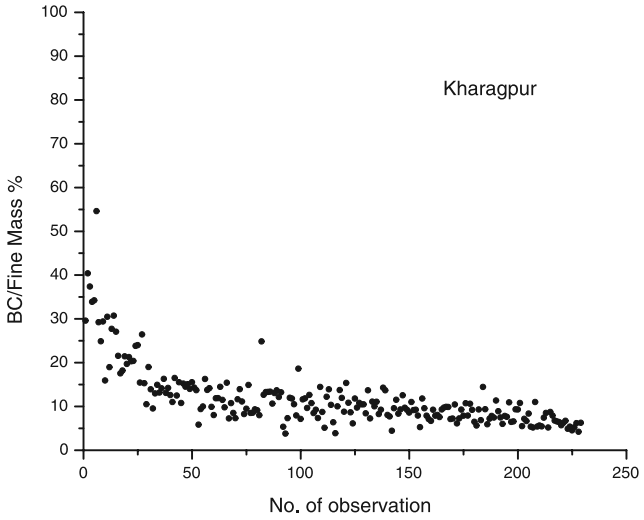

Figure 8. BC/fine mode fraction in the surface aerosol mass concentration derived from simultaneous Aethalometer and QCM measurements.

[14] The near-surface aerosol black carbon (BC) mass concentration measured using the Aethalometer varied between 5 and 25 μg m^{-3} during the period of observation and shows linear relationship with the fine mode fraction of the near-surface aerosol mass concentration. Figure 8 shows the ratio (in %) of the aerosol black carbon mass concentration to the fine mode aerosol mass (aerodynamic diameter < 1.0 μm) concentration measured with QCM against the serial number of observation. The aerosol black carbon percentage was consistently around 10% through out the period of observation.

6. Typical Diurnal Variations

[15] Diurnal variability of aerosol optical depths is important for various applications including satellite aerosol data validation, Radiative-forcing computation, studies of aerosol interaction with humidity, and clouds and also public health [*Smirnov et al.*, 2002a]. In view of the diurnal changes in boundary layer circulation and the presence of local sources the responses of aerosol characteristics to these are examined. Figure 9 shows the diurnal variation of aerosol optical depths at 500 nm on 8 and 9 December 2004. The AOD was around 0.5 on 8 December, but increased to a mean of around 0.8 on 9 December. The near-surface aerosol mass size distributions (measured for 36 hours continuously on both the days) in the nucleation, accumulation and coarse mode (Figure 10) show significant diurnal variability. The aerosol mass concentration in the accumulation mode was more or less the same on both the days when the AODs were measured. However, the nucleation and coarse mode aerosols show a proportionate increase in the mass concentration from 8 to 9 December to account for the higher AODs observed on 9 December. The accumulation and nucleation mode aerosols mass concentrations show a nice diurnal variability with increase in the mass concentrations due to boundary layer subsidence after sunset. The near-surface mass concentrations showed a decrease after sunrise with the increase in surface temperature triggering the build up of convective activity and consequent aerosol ventilation.

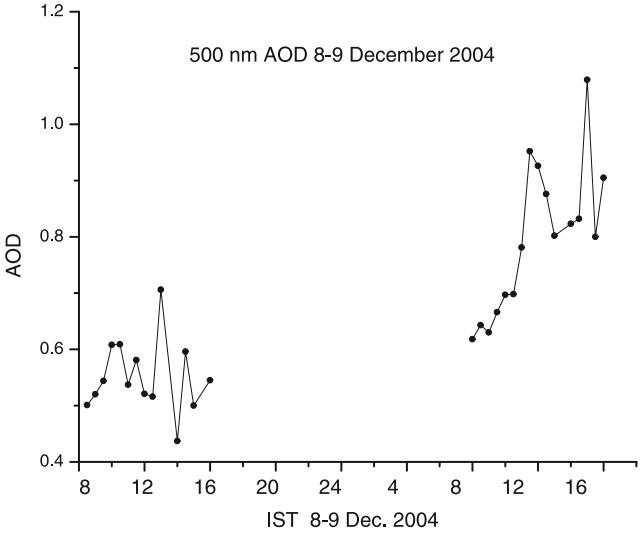

Figure 9. Variation of aerosol optical depth from 0800 LT on 8 December to 1700 LT of 9 December 2005.

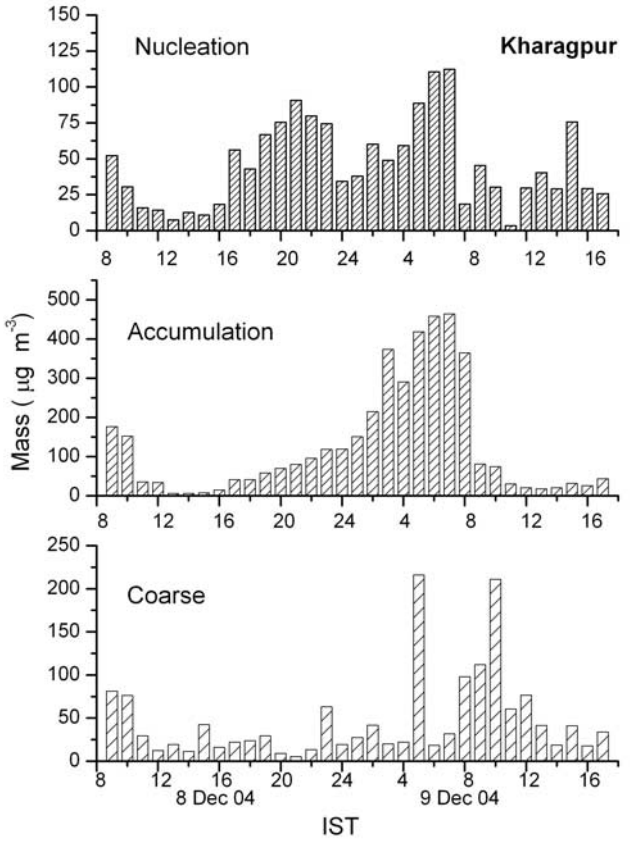

Figure 10. Variation of aerosol mass concentration in the three size ranges, namely, nucleation (aerodynamic diameter <0.1 μm), accumulation (aerodynamic diameter between 0.1 and 1.0 μm), and coarse mode (aerodynamic diameter >1 μm) from 0800 LT of 8 December to 1700 LT of 9 December 2004.

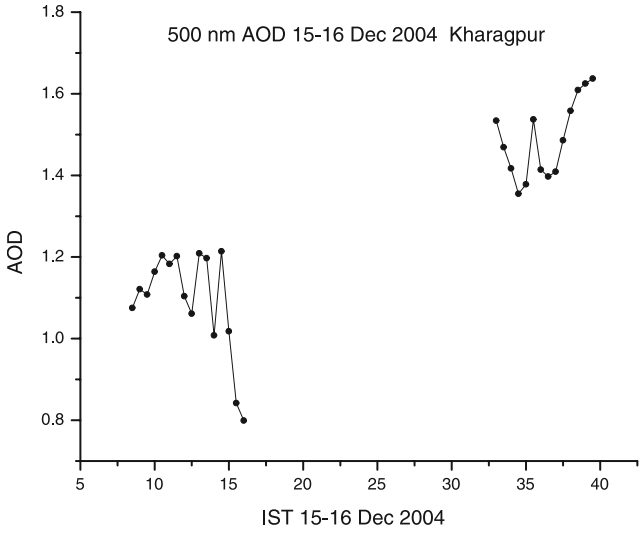

Figure 11. Same as Figure 9 for 15–16 December 2004.

[16] Figure 11 shows another set of two consecutive days: 15 and 16 December 2004. On 15 December the AODs were around 1.1 and the next day it increased to 1.4. However, in this case, the mode classified near-surface aerosol mass in the nucleation and coarse mode shown in Figure 12 does not show any proportional increase while the accumulation mode aerosol shows large increase on 16 December compared to 15 December resulting in increased AOD values on 16 December.

7. Lidar-Derived Aerosol Backscatter Profiles

[17] It is increasingly recognized that global maps of AOD in combination with a qualitative knowledge about aerosol composition (refractive indices) are not sufficient to quantify the impact of aerosols on the physical processes in the atmosphere [*Franke et al.*, 2003]. Vertically resolved aerosol measurements (on a regional and global scale) are required to improve our knowledge about aerosol layering, the causes for this layering and related consequences. Investigations using six wavelength aerosol lidar at Maldives indicated that the AOD in the marine boundary layer was 0.2 and in the free troposphere 0.4 at 532 nm [*Ansmann et al.*, 2000]. Inversions using spectrally resolved particle backscatter and extinction data indicate an effective particle radius of 0.17 μm and considerable absorption by the free troposphere aerosol. The vertical profile of aerosol species has been shown to be a very important factor in determining the overall direct radiative forcing of the species. With sulfate at low altitudes giving the strongest direct radiative forcing (DRF) due to the effects of RH, BC at high altitudes gives the strongest DRF as these aerosol species are much above the cloudy layers of the atmosphere [*Haywood and Ramaswamy*, 1998]. Some times, stratification of aerosol in the nocturnal lower troposphere is fairly common and can be attributed to stratified turbulence in that region [*Parameswaran et al.*, 1997]. Accretion of aerosols occurs in stable regions and depletion of aerosols occurs in turbulent zone embedded in a stable region. Aerosol concentration near the surface is strongly influenced by synoptic atmospheric boundary layer meteorology [*Parameswaran et al.*, 2004]. The altitude structure of aerosol number density shows three distinct zones depending on the prevailing boundary layer features viz., well mixed region, the entrainment region and the upper mixing region [*Parameswaran*, 2001].

[18] Figure 13 shows the aerosol backscatter intensity color maps derived from micropulse lidar data. Each vertical band represents the color map of the day indicated at the bottom between 1800 and 1900 LT. The backscatter data are range and overlap corrected and then corrected for Rayleigh backscatter, and the backscatter intensity plotted in the map represents the aerosol backscatter intensity only. It may be noted that the aerosol mixing height indicates a distinct variation with significant aerosol backscatter up to about 4.5 to 5 km in the early observation period. The altitude up to which significant aerosol backscatter is seen steadily decreased toward the middle of December 2004, indicating the compression of the surface aerosol layer. During the intermittent days when the sky was clear, extended aerosol backscatter up to higher altitudes is seen, for example during 21–22 December 2004. One of the important points to note is the thick surface aerosol layer extending up to 1.5 to 2 km altitude through out the observation period. Figure 14 shows the mean aerosol backscatter intensity at four different altitudes namely 0.5, 1.5, 3, and 5 km. The aerosol backscatter intensity from the surface layer of 0.5 km follows the day-to-day variability in the near-surface aerosol

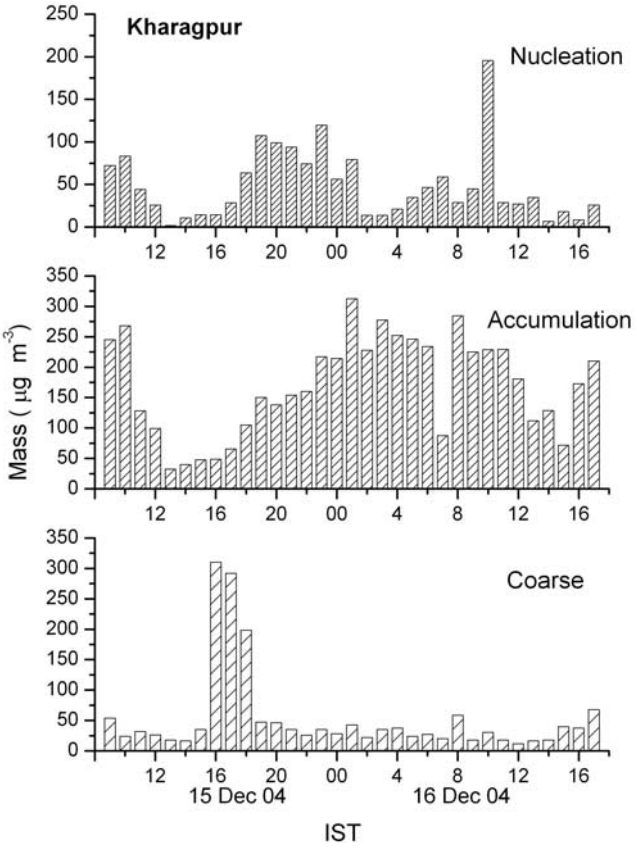

Figure 12. Same as Figure 10 for 15–16 December 2004.

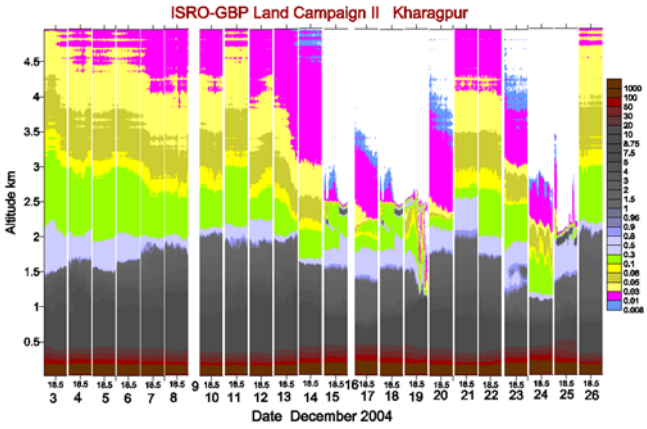

Figure 13. Color map of aerosol backscatter intensity during 1800 to 1900 LT everyday during December 2004 derived from the micropulse lidar data. The gaps on 9 and 16 December 2004 indicate nonavailability of lidar data.

mass concentration measured by the QCM system shown in Figure 5. The variation at 1.5 km more or less resembles a mirror image of the variation at 0.5 km indicating that the changes seen in the near-surface measurements are mainly due to the vertical redistribution of aerosol concentration, i.e., whenever there is a decrease in the aerosol concentration at 1.5 km, there is a proportionate increase at 0.5 km altitude. The backscatter intensity at 3 and 5 km do not indicate any significant variation from day to day except that the concentrations are relatively low during the periods when there is air mass subsidence as indicated by the aerosol mixing heights. The absence of any strong day-to-day variability at high altitudes indicates the absence of any transport of aerosol from nonlocal sources to account for the increase in the aerosol optical depths. Thus it may be inferred that the changes in the aerosol optical depth during the month of December are by and large due to the changes in the boundary layer dynamics and the surface weather and

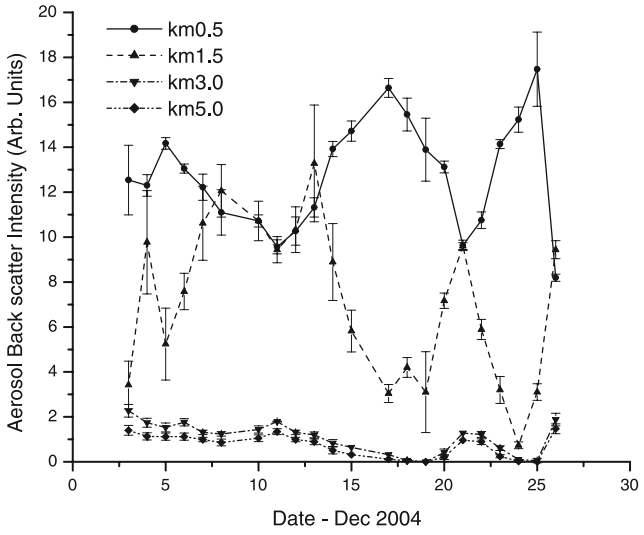

Figure 14. Day-to-day variability of aerosol backscatter intensity at four representative altitudes 0.5, 1.5, 3, and 5 km.

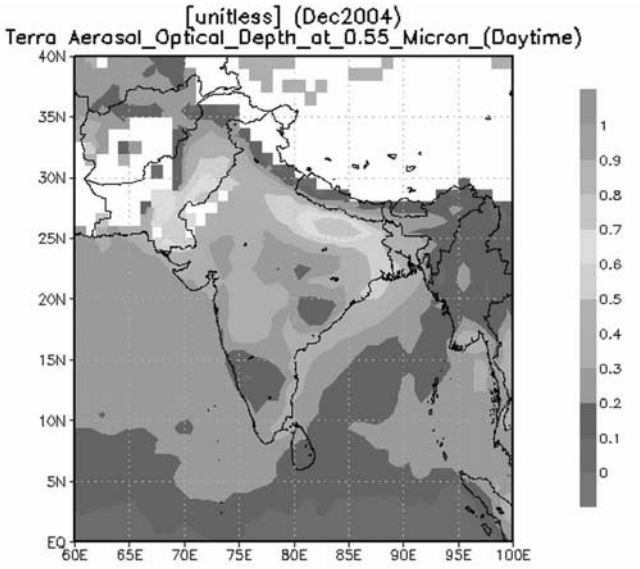

Figure 15. Mean aerosol optical depth map at 550 nm over India for December 2004 derived from MODIS.

that the aerosol vertical distribution is characterized by a thick surface aerosol haze extending up to 2 km.

8. Discussion

[19] The present observations indicate that the aerosol optical depth at the out flow region in the Indo-Gangetic plains is as high as 0.7 during clear-sky conditions. *Ramana et al.* [2004] based on radiometric and Lidar observations at three sites in Nepal reported that over the Himalayan regions, the aerosol optical depth was as high as 0.6 indicating the importance of anthropogenic aerosols. The Moderate Resolution Imaging Spectroradiometer (MODIS)-derived map of AOD over the Indian subcontinent (Figure 15) also shows region of high AOD in the Indo-Gangetic plains. *Smirnov et al.* [2002a] reported a diurnal variability of AOD by 50% at locations dominated by anthropogenic sources while the diurnal variability was less than 10% when the dust aerosol dominates. In the present case the diurnal variability when clear-sky conditions prevailed over the observing site was about 33% with day maximum occurring in the noon hours. When it was hazy, the diurnal variability was around 15% only. This could be due to the low-level boundary layer and consequent pile up of aerosol within the boundary layer due to the absence of convection and efficient aerosol ventilation. The α is a first-order parameter indicative of the general size distribution and the relative dominance of fine versus coarse mode particles. A change in α indicates that there is a change in the size distribution. In the present observation, the α has not fallen below 0.9, indicating the dominance of fine mode particles.

[20] The surface QCM measurements show high aerosol concentrations at the observing site and they show large day-to-day variability. *Franke et al.* [2003] reported that the presence of nucleation and accumulation aerosols indicates the presence of strong local sources. Aging of aerosol particles is believed to lead to a significant shift of accu-

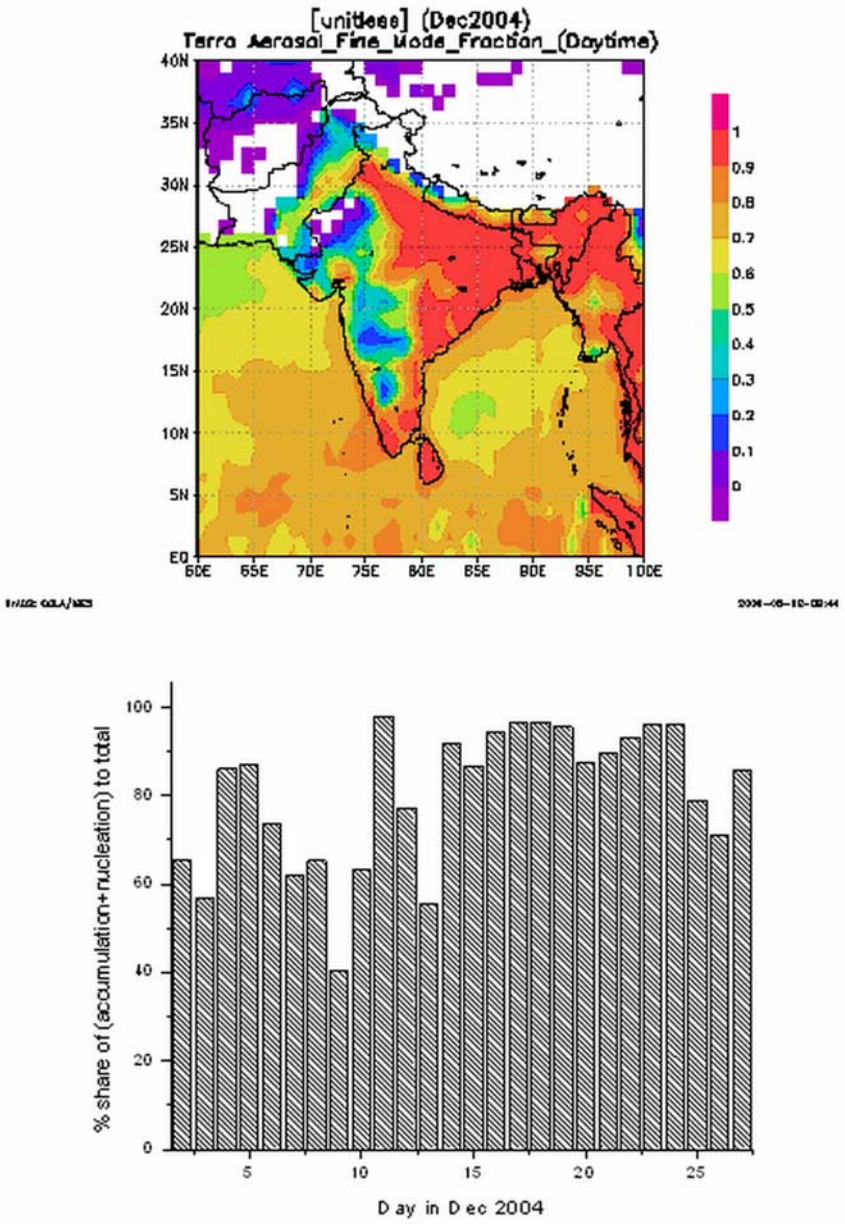

Figure 16. (top) Mean aerosol fine mode fraction over India for December 2004 over India derived from MODIS and (bottom) day-to-day variability in the in situ measured fine mode fraction using QCM.

mulation mode toward larger sizes and to a respective decrease in the Ångström values. In the present data set it is observed that the percent share of fine mode aerosol (nucleation plus accumulation mode aerosol) was highest through out the period of observation. In an urban and highly polluted location like Kharagpur, the anthropogenic sulfate mass resides in accumulation mode size particle [*Boucher and Anderson*, 1995] and hence may account for the dominance of the accumulation mode aerosol at the site. The MODIS-derived aerosol map over the subcontinent shows around 90% fine mode fraction over northern India (Figure 16). The bar diagram shown in Figure 16 (bottom) shows the day-to-day variability of the fine mode fraction from the in situ measurements using QCM system, which indicates more than 85% in fairly good agreement with the MODIS-derived fine mode fraction. During the earlier part of the observation period, when the surface temperatures were high, there was a significant share of the coarse mode aerosols also. The most significant difference between ocean and land surface is the difference in specific heat and surface reflectance [*Satheesh et al.*, 2002]. Land responds to surface radiation flux changes much more quickly than the ocean because of its lower heat capacity. Thus, during clear-sky conditions the land surface responds more quickly to surface solar irradiance, particularly in the dry weather condition as that during winter, leading to the generation of dust aerosol in the alluvial plains which may account for the coarse mode aerosols.

[21] Though there was an overall increase in spectral AODs in both the diurnal observations from the previous day to the following day, as reflected by an increase in 500 nm AOD, there was a contrasting behavior in the near-surface

aerosol characteristics. During the clear-sky period, the typical diurnal pattern (8–9 December 2004) indicates changes only in the nucleation mode aerosol to account for the day-to-day change. During this period, no hygroscopic growth is possible since humidity levels were below the threshold response level and the contribution of local sources account for a proportional increase in both the nucleation and coarse mode aerosols respectively with the almost unchanged pattern of accumulation mode. In contrast on the typical second diurnal pattern (15–16 December 2004) during the hazy sky period (15–27 December 2004) show a large increase in accumulation mode by the next day which could be because of the hygroscopic growth due to compression of the aerosol layer and relatively high humidity levels bringing the system to a saturation level conducive for hygroscopic growth. However, progressive growth did not take place due to high aerosol population which can otherwise lead to sedimentation and fall out mechanisms, keeping the high levels to nucleation and accumulation modes which are important when viewed in the context of aerosol transport.

[22] The lidar measurements indicate a strong aerosol loading in the near-surface layer up to ~2 km. *Rasch et al.* [2001] reported from an aerosol assimilation model that the plume from Kolkata is deeper than the one from Mumbai and indicated that very strong outflow occurs up to 1 km in altitude and its only slightly weaker at 2.5 km. After the plume reaches the center of BOB it often merges with an equal amount of aerosol from SE Asia and travel around the southern tip of India across Srilanka and over to Arabian Sea. Aerosol outflow at 2.5 km is somewhat weaker and transport circulation is more strongly confined to the Indian continent and it does not extend so far in to BOB. Most of the strong transport of aerosol from the Kolkata/Bangladesh region occurs at the surface and much of the aerosol continues eastward and out of the domain, rather than veering southward and westward. The near-surface aerosol layer is approximately 1.5 km thick and then a dispersive layer extending up to 5 km as observed in the vertical profiles. *Satheesh et al.* [1999] reported that the value of the scattering coefficient estimated for tropical Indian Ocean seems to be higher than those for other sites including the coastal site at Washington, which they opined be due to significant emissions from the subcontinent and the confinement of aerosols in the boundary layer, both of which will enhance the near-surface scattering coefficient. In this present case, due to the low-temperature and low-level boundary layer, there is a confinement of aerosol in the near-surface layer.

[23] Colocated micropulse lidar observations and the backward trajectories indicate the absence of any major aerosol transport from the sources of nonlocal origin to contribute to the high aerosol abundance. The boundary layer dynamics associated with the surface meteorology more or less account for the observed day-to-day variability. Since the measurements are made at the outflow region into the Bay of Bengal, one of the significant contributors to the transport of aerosol into the coastal Indian Ocean, Bay of Bengal and Arabian Sea, it is worth investigating the forward trajectories to locate the regions affected by this high polluted air mass in the northern India.

[24] Transport of aerosol into the Bay and Bengal occurs from the Indian subcontinent and Southeast Asia and the high AODs and aerosol mass concentrations observed during the local winter NE monsoon season are associated with the offshore flow. *Ramachandran and Jayaraman* [2002] reported that the height of aerosol transport into this region appears to be below 750 hPa and that the anthropogenic contribution to AODs measured over the Coastal India, Arabian Sea and tropical Indian Ocean is around 95%, 93% and 74% respectively. The forward trajectories for the present observational period were evaluated at three different altitudes namely 500 m, 1.5 km and 3.0 km above mean sea level and a few typical cases were shown in Figure 17. Table.1 shows the statistics of the forward air mass trajectories, which indicate that out of the 25 cases studied the air mass from the north Indian polluted region at 500 m level first enters the Bay of Bengal in 17 cases, reenters the Indian subcontinent south of about 18°N latitude, travel across the continent and enters the Arabian Sea. Even at 1.5 km level also, on majority of occasions, the air mass flow follows the above path. In a few cases at 1.5 km level and majority of cases at 3 km level, the air mass flows into tropical Indian Ocean via Bay of Bengal.

[25] Atmospheric circulation and aerosol lifetimes are the dominant factors controlling the spatial distribution and transport of aerosols. The large high-pressure system that forms over the central India gives rise to Indian dry season and generates a persistent north easterly flow [*Krishnamurti et al.*, 1998]. This offshore flow does not penetrate deep into the BOB which results in large spatial gradient in AOD observed near NW Bay of Bengal. Generally, the AOD in BOB is comparable to that of the Arabian Sea, with high values during January. However, coastal values are higher than those in the Arabian Sea, which is associated with large spatial gradients and the AOD rapidly decreases away from the coast [*Rajeev et al.*, 2000]. In contrast, the AOD plumes associated with south east Asia are higher in March compared to the Indian one seen in January. *Ansmann et al.* [2000] reported the observation of a couple of cases when Indian aerosol plumes were observed over Hulule in Maldives during February to March 1999 with a six wavelength lidar. *Yu et al.* [2000] from a study of aerosol radiative properties in the south eastern United States reported that the major portion of atmospheric aerosol which makes an important contribution to the optical depth is located in the lower 1 km boundary layer of the troposphere and *Hegg et al.* [1997] reported that the lower 4 km troposphere contribution is over 90% off the Mid-Atlantic coast of the United States.

[26] *Niranjan et al.* [2005], during a mobile land campaign in February 2004, made a comprehensive set of measurements on aerosol physical properties in the north eastern parts of peninsular India at 36 locations with latitude extent of 16.5°N to 21.5°N with longitudinal coverage from 78°E to 86.3°E. They reported that the aerosol optical depths, size index "α" and the near-surface aerosol mass concentrations indicate a relative abundance of accumulation mode aerosols in the eastern coastal and southern latitudes. The air mass pathways derived from the back trajectories indicate that the higher population in the accumulation mode and consequently higher optical depths in the southern locations on the peninsular India could be due

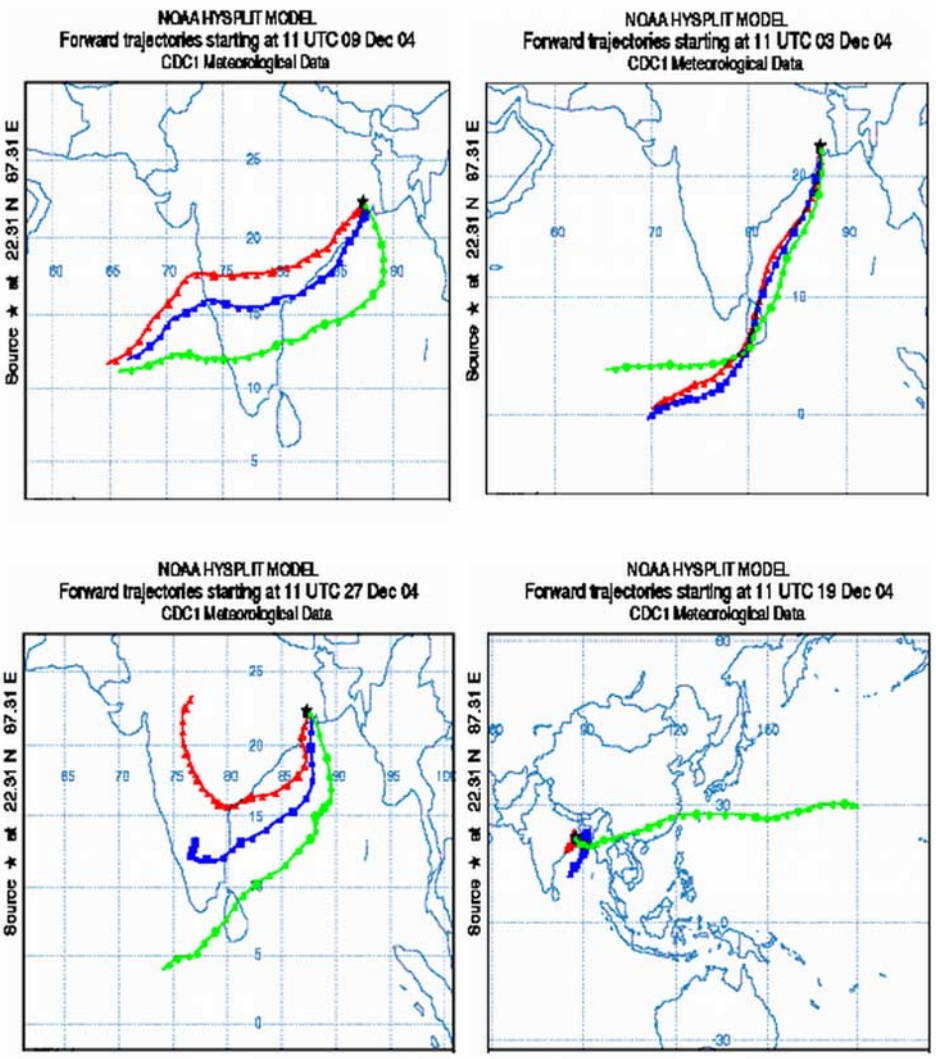

Figure 17. Forward trajectories of the air mass pathways from Kharagpur during the period of observation showing the probable destinations of the Indian haze. The probabilities are given in Table 1.

to the transport of aerosol from the polluted north Indian region via the oceanic region over the Bay of Bengal where significant particle growth is expected increasing the population of accumulation mode aerosols over the southern locations in the peninsular India when the air mass reenters the land in its transit to Arabian Sea. Since the air mass trajectories at the surface level up to approximately 1.5 km are toward the Arabian Sea via BOB and the south Indian peninsula, the offshore flow does not penetrate deep into the Bay of Bengal. This accounts for the large spatial gradients observed in the NW Bay of Bengal.

9. Summary

[27] This paper reports the first results on the observation of aerosol physical properties at Kharagpur located in the Indo-Gangetic plains at the vent of the outflow regions from northern India into Bay of Bengal during the winter month of December 2004. The salient features are as follows:

Table 1. Details Showing the Statistics of the Probable Destinations of the Indian Haze at Three Representative Altitudes

Altitude, m	Via BOB, Subcontinent, Into Arabian Sea (Figure 17, left top)	Via BOB Into Indian Ocean (Figure 17, right top)	Via BOB Into Subcontinent (Figure 17, left bottom)	Into BOB (Figure 17, right bottom)	Into Subcontinent	Via BOB Into Indonesia (Figure 17, right bottom)
500	17	1	4	2	1	0
1500	13	6	4	1	0	1
3000	7	10	0	0	0	8

[28] 1. The aerosol optical depths were high with a mean AOD of 0.7 at 500 nm. The earlier part of the month was characterized by clear-sky condition while the later part of the month was hazy.

[29] 2. The near-surface mass concentrations were also high with a mean total mass concentration of 100 μg m^{-3} during clear-sky conditions. The day-to-day variability in the aerosol mass concentration shows an inverse relationship with the boundary layer height.

[30] 3. The day-to-day variability is weighted by the accumulation mode aerosol indicating the potential high lifetime of the aerosol to participate in long distance transport.

[31] 4. The lidar-derived aerosol backscatter intensity at altitudes above and below the boundary layer show opposite variation indicating a vertical redistribution of aerosols that account for the day-to-day variability in surface aerosol mass concentrations.

[32] 5. The lidar backscatter intensity profiles indicate a thick aerosol layer extending up to an altitude of about 2 km over the location.

[33] 6. The forward trajectories with source location at the observing site indicate high probability for the transport of the plume into Arabian Sea via Bay of Bengal and peninsular India.

[34] 7. Earlier observations over peninsular India indicate the presence of higher concentrations of accumulation mode aerosol that have their sources in the northern India confirming the transport of the north Indian haze into the oceanic regions via the southern peninsular India, which also accounts for the large spatial gradients in the Bay of Bengal region as the plume does not penetrate deep into the Bay of Bengal region as indicated by the air mass trajectories, before reentering the peninsular India.

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