Micro pulse lidar observation of high altitude aerosol layers at Visakhapatnam located on the east coast of India

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[1] Aerosol back scatter profiles obtained using a micro pulse lidar at Visakhapatnam, a station located on the east coast of peninsular India show certain high altitude aerosol layers during the months of March/April 2005, 2006. Co-located aerosol optical depth measurements show an increase in AOD by 0.05 to 0.25 during the event when the layers were observed. The prevailing meteorology does not indicate any possible local entrainment of aerosol leading to the formation of elevated layers due to boundary layer dynamics. The 7 day back trajectory analysis shows that the possible origin of the layers could be from Arabia in 60% of the cases while it is from Indian sub-continent during the rest of the events. When the air mass flow is from the Indian sub-continent, there is a proportional increase in MODIS derived aerosol column fine mode fraction though it is not observed at the surface level. During the events when air mass flow is from Arabia, such an increase in column fine mode fraction was not observed but the angstrom size index which is a measure of the aerosol size distribution was low indicating that the elevated layers of Arabian origin could contain significant fraction of dust aerosol. **Citation:** Niranjan, K., B. L. Madhavan, and V. Sreekanth (2007), Micro pulse lidar observation of high altitude aerosol layers at Visakhapatnam located on the east coast of India, *Geophys. Res. Lett.*, *34*, L03815, doi:10.1029/2006GL028199.

1. Introduction

[2] It is well recognized that ignoring vertical layering of aerosols can lead to several uncertainties in aerosol remote sensing [*Franke et al.*, 2003]. Current emphasis is on the observation of physical properties of the atmospheric boundary layer aerosols and elevated aerosol layers which are most relevant to radiative forcing applications. Lidar measurements are valuable in aerosol studies in that they potentially supply vertical information on aerosol optical properties. Lidar profiles sampling the air mass advected from the Indian sub-continent show multiple layers present over the Indian ocean as a result of convection and long range transport of aerosol originating from arid and semi arid regions of the world [*Müller et al.*, 2001; *Ramanathan et al.*, 2001]. At times the air mass shows 3 km deep pollution layer above the boundary layer [*Ansmann et al.*, 2000]. Such elevated aerosol plumes were also observed over the northern India, particularly during winter season due to dry convective lifting of pollutants at distant sources and subsequent horizontal upper air long range transport [*Ramana et al.*, 2004]. Aerosol layers found above the boundary layer could be transported several thousands of km without significant removal and can contribute significantly to the column aerosol optical depth, at times more than the boundary layer [*Franke et al.*, 2003]. From aerosol assimilation model, *Rasch et al.* [2001] reported that three points of entry are found for the anthropogenic aerosols to the INDOEX region namely, a strong near surface southward flow from Mumbai, a deeper plume flowing south and east of Kolkata and a westward flow originating from South East Asia and entering BOB. All these plumes are strongly modulated by a low frequency change of the meteorological regime associated with the Madden Julian Oscillation. Considering the importance of aerosol layers, a qualitative study has been carried out for the first time on the observation of high altitude aerosol layers at Visakhapatnam, an urban station on the Bay of Bengal coast in the eastern peninsular India using a micro pulse lidar and the results are reported here. The site located on the east coast of India is in the air mass pathway from the Indian sub-continent into the surrounding oceanic regions and hence the study assumes importance in radiative forcing estimates over the Asian region. The results presented indicate for the first time that the air mass advecting over the eastern coast of India into Bay of Bengal not only contains the anthropogenic contribution from the Indian sub-continent but also at times contains the plumes advecting from Arabian regions with significant contribution of dust aerosol.

2. Data and Methodology

[3] A Science and Engineering Services Incorporated micro pulse lidar (MPL) model 1000 was installed at Andhra University, Visakhapatnam located on the Bay of Bengal coast in the eastern peninsular India in the year 2005. The system employs an optical transceiver that acts as both transmitter and receiver (telescope) consisting of a pulsating Nd:YAG/Nd:YLF laser at 532 nm, Si-APD photon counting detector, signal processing unit, and data processor. The laser pulse duration was 100 ns, which gives a vertical resolution of 30 m. The range corrected, normalized lidar return signal for one transmitted laser pulse is a combination of the back scatter energy from the Rayleigh and aerosol components. Assuming that the aerosol tends to be fairly homogeneously distributed in the horizontal direction, we have used the horizontal retrieval method [*Collis*, 1966] for evaluating the overlap correction factors for the MPL back scatter intensity. The overlap occurred at an altitude of 1.8 km for the present transceiver. The micro pulse lidar used in the present study transmits pulse energy of 6–7 μJ per pulse with duration of 100 ns. The PRF was 2500 shots and each profile is derived with an averaging for

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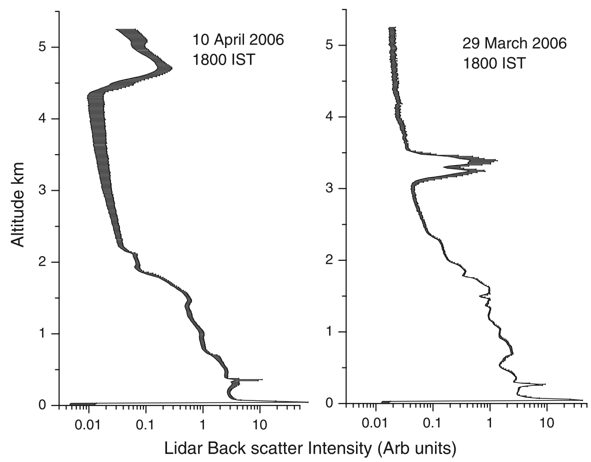

Figure 1. Vertical profiles of lidar back scatter intensity on 10 April 2006 and 29 March 2006 showing aerosol layer at an altitude above 4 km and 3 km, respectively.

10 seconds. Thus, one profile is the average of 25000 shots. Therefore, significant back scatter was obtained from altitudes with no aerosol contribution due to the high energy of the transmitted pulse. We have averaged the overlap corrected profiles for a time duration of 15 minutes in the range bins representing the altitudes range of 25 to 30 km considering this as the no-aerosol zone and evaluated the system constant using the MPL back scatter intensity and the known air density model data of *Sasi and Sengupta* [1979] for the Indian latitudes following the aerosol free region approach [*Fernald*, 1984]. With the evaluated constants we have corrected the back scattered signal for Rayleigh contribution taking the air density data for lower altitudes from *Sasi and Sengupta* [1979]. The colour maps shown in this article are the back scatter intensity after range, overlap and Rayleigh correction and represent the aerosol back scatter intensity only as a function of altitude.

[4] Co-located measurements on aerosol spectral optical depth (AOD) using a Microtops II sun photometer and near surface mass size distributions using a Quartz Crystal Microbalance (QCM) have been used to contrast the aerosol column integrated and the surface features. The measurements included (1) the aerosol spectral optical depth at 5 wavelengths centered about 380, 440, 500, 675, and 870 nm using a Microtops sunphotometer (Solar Light Co, USA), with a Global Positioning System (GPS) receiver attached with the Photometer to provide information on the location, altitude, and pressure; and (2) near surface aerosol mass concentrations using a ten channel Quartz Crystal Microbalance (QCM) Impactor (California Measurements Inc., USA), whose 50% aerodynamic cut-off 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 liters per minute and sampled for duration of 300 seconds for each measurement.

3. Results and Discussion

[5] In Figure 1 are shown the raw profiles of range corrected lidar back scatter intensity as a function of altitude for 10 April 2006 and 29 March 2006. It may be seen that strong aerosol back scatter was observed from an altitude of 4.5 to 5 km on 10 April 2006 and between 3 and 4 km on 29 March 2006 indicating high altitude aerosol layers. We have analyzed the data for all the available periods between November 2004 to May 2005 and March 2006 to June 2006. All the data was normalized to a transmitted power of 7 μJ per pulse. In all, we have observed about 20 clear cases of high altitude layers during the period of study and the heights of the observed layers varied between 1.6 km and 5 km with more probable occurrence above 2 km. Figure 2 shows the colour map of the range, overlap and Rayleigh corrected lidar back scatter intensity representing the aerosol back scatter for two representative days without the presence of high altitude aerosol layer on 23 March 2006 and with the presence of aerosol layer above 4 km on the 10 April 2006 respectively. It is a general observation that clouds are not transparent to laser and during the observation of the layers aloft, we were able to get regular back scatter from higher altitudes also. *Ansmann et al.* [2000] from vertical profiling of the Indian aerosol plume with a six wavelength lidar at Hulhule in Maldives reported that the free tropospheric aerosol layer contributed to 66% to the

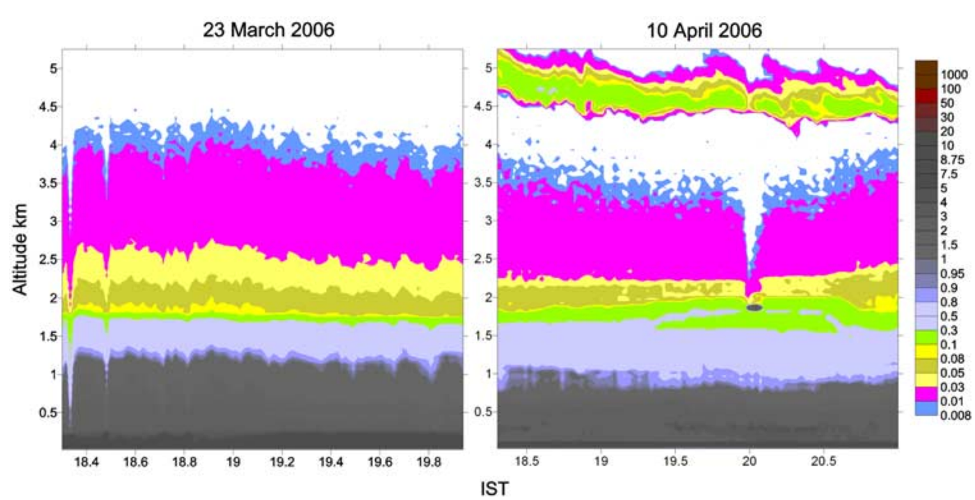

Figure 2. Colour map of aerosol back scatter intensity without aerosol layer (23 March 2006) and with approximately 1 km thick layer at 4.5 km altitude (10 April 2006).

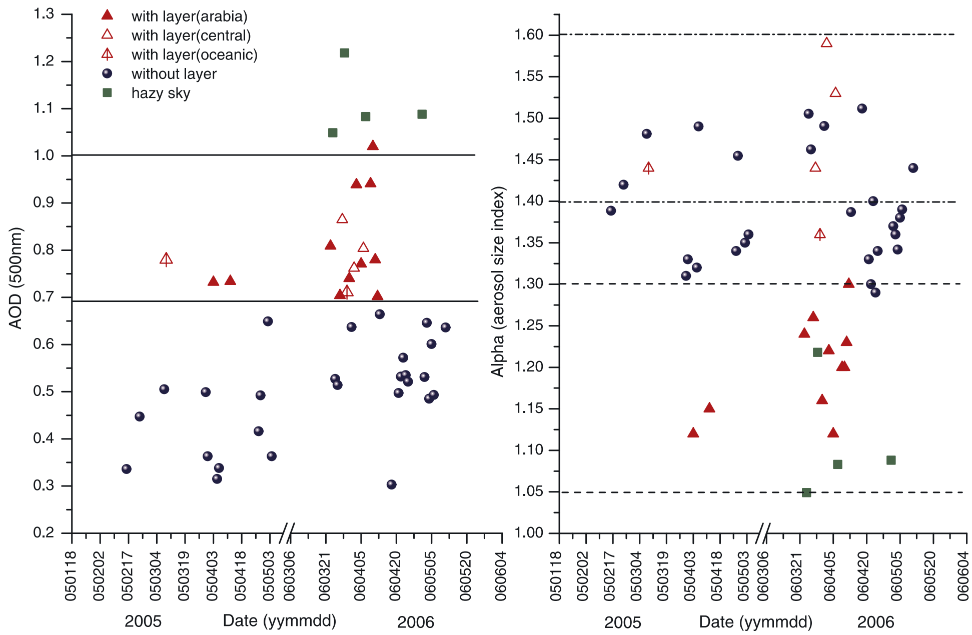

Figure 3. (left) Aerosol column optical depth at 500 nm measured with ground based sun photometer during cases with no layer (solid dots), with layer (triangles), and during hazy condition (solid squares). (right) Corresponding alpha values show air mass flow from Arabian region (solid triangles), air mass from central/peninsular Indian (open triangles), and air mass from Bay of Bengal (crossed triangles).

column optical depth. Further, the height dependence of lidar ratio indicates several layers of different aerosol types. *Ramana et al.* [2004] also reported that MPL profiles over Khatmandu in northern India show a layer at 0.3 km and another at 1.3 km (~2.6 km MSL). The former is possibly due to the aerosols generated locally while the high altitude one is most likely due to the convective lifting of aerosols originating at distant sources and subsequently by horizontal upper air transport. Secondly cirrus clouds are frequently observed at altitudes of 9 km and above, more frequently in winter months and the aerosol layers reported here are not due to cirrus. *Parameswaran et al.* [2001] also reported that cirrus occurs approximately 2 km below tropopause.

[6] *Parameswaran et al.* [1997] from an observational study of night time aerosol concentrations in the lower atmosphere at a tropical coastal station reported that accretion of aerosol occurs in a stable atmosphere sandwiched between two turbulent regions which are normally observed within the boundary layer. Stratified turbulence in a stable atmosphere tends to smooth out concentration gradients, causing formation of aerosol depleted regions which ultimately are observed as aerosol layers within the nocturnal boundary layer. In winter season, during day time the surface gets heated due to clear sky conditions and in the evening due to sudden cooling of earth's surface after sunset leads to the formation of stable layer close to the surface and elevated residual layer of enhanced aerosol concentrations. However such events occur during the winter months and at altitudes slightly higher than the boundary layer. But the present observations indicate the presence of high altitude layers in the free troposphere, much above the boundary layer and not during winter months. We have also investigated the prevailing meteorology in each case which does not indicate any possible entrainment of aerosol due to boundary layer dynamics.

[7] In order to investigate the same in conjunction with the surface aerosol physical properties and column integrated aerosol optical depths, we have used the co-located data on aerosol column optical depths obtained using a Microtops sun photometer and a Quartz Crystal Microbalance. Figure 3 (left) shows the aerosol column optical depth at 500 nm observed during daytime when the aerosol layers were observed in the lidar data. Also presented are the AOD data for the days in the month when the layer was observed. It may be seen that when elevated layers were observed in the lidar data, the column AODs were more with the difference ranging from 0.05 to as large as 0.25. Very hazy skies are characterized by AOD more than 1.0. The lidar derived contribution of aerosol extinction due to the layers match with those observed from the column AODs within ±20%. It is also observed that the contribution of layer extinction derived from lidar depends on the thickness of the layer and the relative back scatter intensity signifying the aerosol number density in the elevated layer. The near surface total aerosol mass concentration shown in Figure 4 indicates that there is no clear difference in surface mass concentration between the days on which layers were observed compared to days without elevated aerosol layers. This indicates a decoupling of column AOD from the surface features. However, MODIS derived column fine mode fraction [*Kaufman et al.*, 1997] in some cases does indicate an enhancement. The MODIS derived fine mode fraction is a product from spectral optical depth (AOD) and hence corresponds to columnar measurements while the QCM measurements reported here reflect the near surface features. In order to assess the probable source regions of the elevated layers, we have investigated the 7 day back trajectories for all the cases of elevated layers at the mean height of the layer with Visakhapatnam as the source point. The results which are consolidated in Table 1 indicate that

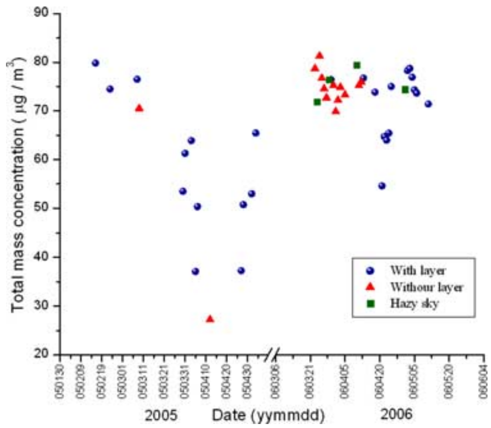

Figure 4. Near surface aerosol total mass concentration showing typical cases with layer (solid triangles) and without layer (solid dots).

in 60% of the cases the layer origin seems to be from Arabia as the back trajectory calculations indicated that at the layer altitudes the air masses advected from Arabian regions, while in the rest of the cases it could be either from Indian sub-continent or from the Bay of Bengal as shown in Figure 5. But, whenever there is an indication of transport from Arabia, the air mass travels over the Indian sub-continent also before being observed at the site. Therefore, it is difficult to identify whether the layer constitutes of dust aerosol if it is coming from Arabia as in its transit it could also pick up the anthropogenic aerosol over the continent. In certain cases mixing of dust particles with boundary layer aerosols reduces dust signatures and makes it difficult for the separation of the dust particles from those of mostly urban origin. The frequent co-existence of urban, continental, dust and marine aerosol makes it difficult to provide distinct information on the optical properties of individual types of aerosol using lidar measurements [*Balis et al.*, 2004]. This has prompted us to investigate whether the elevated layer consists of a dominant fine mode aerosol or the dust aerosol. The AOD data at five wavelengths namely 380, 440, 500, 675, and 870 nm measured using the Microtops sun photometer are analyzed by fitting the Angstrom power law which is of the form $\tau = \beta\lambda^{-\alpha}$, where α is the wavelength exponent which is the size index and β is the turbidity parameter which is a measure of aerosol loading and λ is the wavelength in μm and the alpha values are shown as in Figure 3 (right). It is observed that whenever the air mass transport is from Arabia there is a marginal decrease in the value of Angstrom size index as shown in Figure 3 and Table 2 (α was in the range of 1.05 to 1.3 in cases of transport from Arabia with a mean of 1.2)

Table 1. Statistics Showing the Air Mass Pathways When Layers Were Observed

Altitude	Occurrence of Transport, % From Central India	From Arabia	From Bay of Bengal
1 km above mean layer altitude	40	50	10
At mean layer altitude	25	60	15
1 km Below Mean Layer Altitude	55	35	10

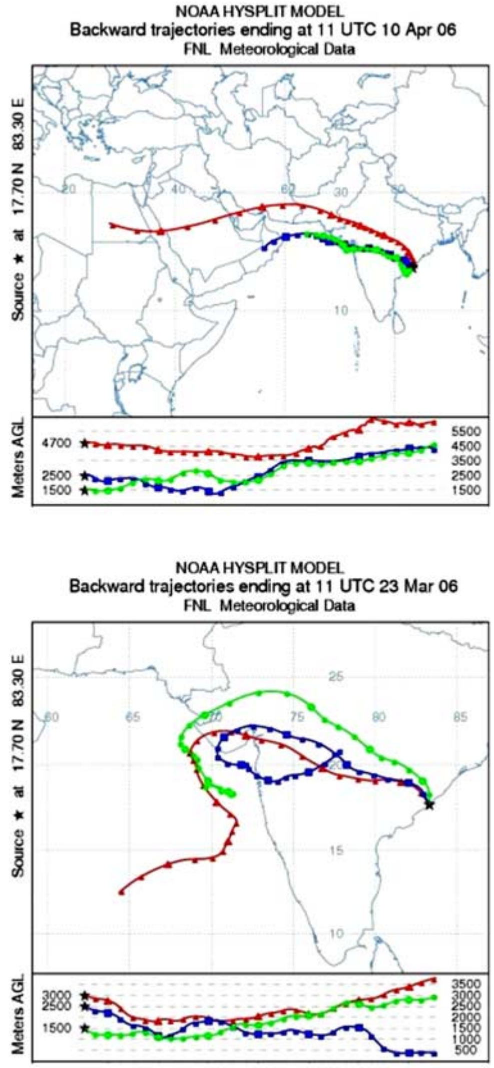

Figure 5. 7 day HYSPLIT back trajectories showing (top) the air mass pathways from Arabian region (10 April 2006) when alpha value was relatively lower and (bottom) when air mass pathways are from central India (23 March 2006) when column fine mode fraction showed an increase.

relative to the size index when the trajectories indicate an air mass origin from the Indian sub-continent (with α values in the range of 1.4 to 1.6). This indicates that there could be a significant fraction of coarse mode aerosol when the air mass showing elevated layers is from Arabia while the increase in the optical depth for cases of elevated layers with origin over India indicates the dominance of the fine mode fraction aerosol. *Menzies et al.* [2002] also reported from observations using multi wavelength air borne lidar that their results are in agreement with the earlier observations that the dust survives long range transport. The cases when the layer advected from the Indian sub-continent agree with the cases which show relatively higher column fine mode fraction derived from MODIS as indicated in Table 2. These results have implications in the aerosol radiative forcing applications particularly in the context of ongoing current scientific interest in the Asian regions since the site where the observations were made is in the air mass

Table 2. Transport Wise Mean Values of Aerosol Size Index α, Column Fine Mode Fraction, and Surface Fine Mode Fraction

Air Mass Origin	α	Modis Derived Fine Mode Fraction	Surface Fine Mode Fraction From QCM
Arabia	1.2	0.79	0.66
Central India	1.52	0.94	0.64
Bay of Bengal	1.4	not available	0.57

outflow pathway from the Indian sub-continent into the adjoining oceanic region.

4. Summary

[8] Aerosol back scatter vertical profiles measured using a micro pulse lidar at Visakhapatnam located on the east coast of India show high altitude aerosol layers above the boundary layer in the height region between 1.6 to 5 km during the summer months of March – April 2005, 2006. Co- located column optical depth measurements indicate an increased AOD at 500 nm by 0.05 to 0.25 during the presence of such layers, while the surface aerosol mass concentrations measured during the presence of the layers do not show a proportionate increase. The extinction coefficients derived from MPL back scatter profiles match with column AOD observations using a Microtops sunphotometer. The 7 day back trajectories analysis at the level of the layers indicate that the air mass origin forming the layers is from Arabia during 60% of the case while in the rest it is either from the Indian sub-continent or from Bay of Bengal. In the presence of layers with air mass origin from Arabia the aerosol size index α derived from spectral AODs was lower in the range 1.05 to 1.3 while in other cases with air mass origin from the Indian sub-continent, the size index was more than 1.4. This feature when viewed with the observation that the surface aerosol mass concentration did not show proportionate increase suggests that during the events of layer with air mass origin from Arabia, the column aerosol could comprise of a significant fraction of dust aerosol in the layer.

[9] **Acknowledgments.** This work is supported by Department of Science & Technology, Govt. of India and Indian Space Research Organisation under Geosphere – Biosphere Programme. The back trajectories were produced with HYSPLIT from the NOAA ARL Web site (available at http://www.arl.noaa.gov/ready/hysplit4.html/).

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