Interplay between Aerosol, Cloud and Precipitation: Evidence from Dual Polarization Micro Pulse Lidar Profile Observations

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ABSTRACT

The significant role of atmospheric aerosols in modulating tropical clouds has far reaching consequences on weather and climate. These aerosol effects are poorly quantified and represent the greatest uncertainty in our understanding of the climate system. Aerosols, in indirect way, tinker with size, shape and location of clouds and how much rain these clouds produce. The changes in number concentration of cloud condensation nuclei (CCN) have significant impact on the micro-physics of clouds, precipitation and thus climate. Taking into account the immense role of clouds and aerosols in regulating the thermodynamics/dynamics of weather and climate over tropics, it is worthwhile to have any additional information from location-specific observations of both direct and indirect methods. In this paper, the results of a comprehensive study made by utilizing an autonomous dual polarization micro pulse lidar (DPMPL) that has been in regular operation at the Indian Institute of Tropical Meteorology (IITM), Pune, India, are reported on the coupling processes between aerosols and clouds in a monsoon environment. The polarization lidar back-scattered signal strength profiles up to about 3 km with vertical range resolution of 2.4 m, recorded on some typical experimental days during the south-west monsoon months of 2007 and 2008 have been used to investigate (i) aerosol-cloud interactions, (ii) aerosol-precipitation relationship and (iii) cloud-free and in-cloud turbulence vertical structures. The results reveal that the sub-cloud layer contributes maximum to the CCN within the cloud cells; and intense in-cloud turbulence as compared to the cloud-free regions over the experimental site. The study also points out cloud dissipation after drizzle formation and delay in the production of fresh CCN after the wet removal – a phenomenon, popularly known as “Recharging of the Atmosphere”.

1. INTRODUCTION

Aerosols in the troposphere have broad impact ranging from human health effects to global climate change. Scattering and absorption characteristics of aerosols have a variety of implications in the troposphere (i.e. seeding tropospheric clouds and formation of haze and fog, thereby re-distributing the incoming solar flux and the infrared terrestrial emission), and altering the radiation balance of the earth system [1]. Tropospheric aerosol research deserves special attention because of its multi-functional role in the aerosol-atmosphere interaction, deriving various feedback mechanisms. Depolarization lidars are widely used for the study of aerosols and clouds because of their ability to discriminate not only ice from water but also spherical particles from particles of irregular shape [2]. Because the cross-polarized component can only arise from the multiple scattering processes, observation of this component can provide direct measure of the multiple scattering taking place in the medium [3]. The lidar back-scatter intensity variations have also been used to determine in-cloud and cloud-free turbulence [4] in terms of vertical distributions of optical refractive index structure parameter, C_n^2 in the absence and presence of drizzle. Here, we present some typical results obtained with autonomous DPMPL during cloudy / drizzle atmosphere, delineating aerosol-cloud-precipitation interaction and turbulence structures in the monsoon environment.

2. METHODOLOGY

The lidar system (Foretech Model DPMPL 0.3^c) located at Indian Institute of Tropical Meteorology (IITM), Pune (18^o 32’ N, 73^o 51$'$ E, 559 m AMSL), developed based on uni-axial, mono-static micro pulse lidar concept, with an Nd:YAG (second harmonic, 532 nm) laser energy switching between co- and cross-polarization states alternatively at a speed of about 1 KHz is operational since 2005. The details of the lidar system and data analysis procedure are described elsewhere [5]. In order to address the above issues, the lidar experiments were conducted on some selected days in the monsoon seasons of 2007 and 2008. The lidar profiles were acquired for every minute in real-time mode and the necessary corrections for background and range were carried out. The interaction (in vertical) between aerosols and clouds is studied by estimating the ratio between back-scattered intensity within and below the cloud cells (sub-cloud region extending from ground to the cloud-base) were integrated separately. The association between cloud

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condensation nuclei (CCN) and precipitation (drizzle in the present case) was studied to bring out an insight into an interesting phenomenon, viz., 'Recharging of the Atmosphere'. From the depolarization information, the anisotropy nature of cloud droplets has been examined. The lidar back-scatter intensity data have also been utilized to compute the optical C_n^2 before and after the onset of drizzle, following the formulations developed by Tatarskii, 1961.

3. RESULTS AND DISCUSSION

3.1 Aerosol-Cloud Interaction

Figure 1 depicts the association between cloud thickness (histogram) and cloud to sub-cloud ratio (CSR) (solid curve), recorded on 09 June 2008. The

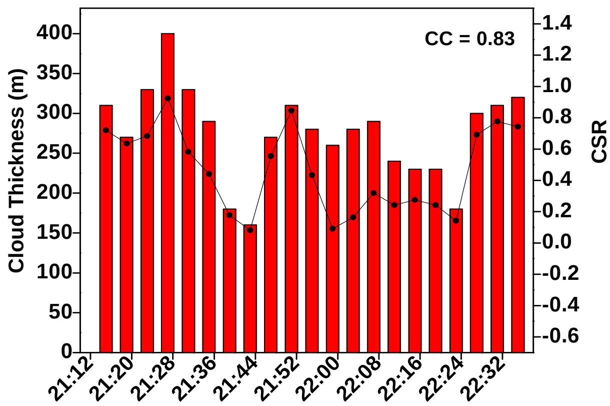


Figure 1. Time evolution of cloud thickness versus CSR observed with DPMPL on 09 June 2008.

correlation coefficient (CC) between these two parameters is also indicated in the figure. It is evident from the figure that higher the CSR, more is the cloud thickness. The higher and significant CC observed in this case indicates CCN enhancement in the cloud cover at the expense of decrease of CCN concentration in the sub-cloud region. This finding has a direct bearing on the growth process and persistence of cloud cover which supplements the cloud dissipation due to scavenging by wet deposition or rain-out. The cloud droplet number density depends predominantly on the relationship between the updraft velocity, availability of moisture, the critical activation radius, collision-coalescence etc. The impact of all these environmental parameters on the ratio of sub-cloud and in-cloud air mass is assumed to be negligible.

3.2 Aerosol-Precipitation Relationship

Two special lidar experiments, one on 03 July 2007 and the other on 06-07 June 2008 were conducted. On these both occasions, the sky over the experimental site was totally covered by low-level stratus clouds. The time evolution of lidar backscatter intensity on these days is shown in Figure 2 (A) and (B). On 03 July, the cloud cells can be seen in the

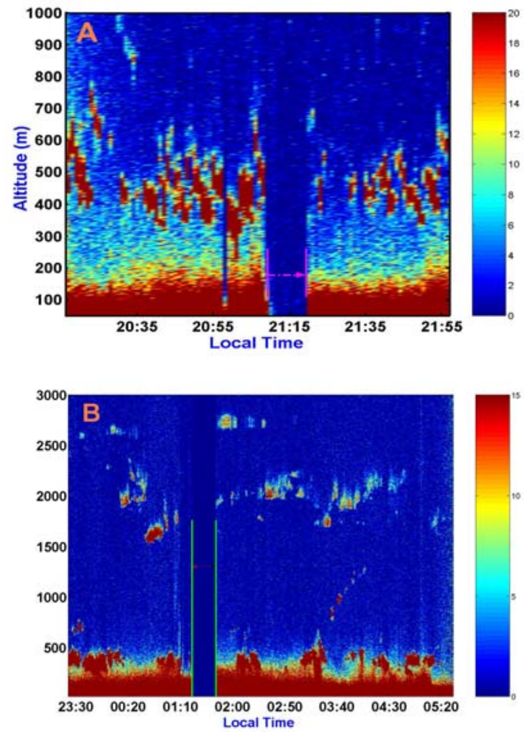


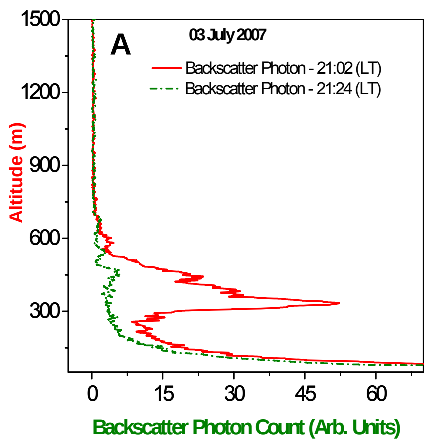
Figure 2. The height-time-intensity (HTI) plot of aerosol backscatter profiles obtained on (A) 03 July 2007 and (B) 6-7 June 2008. The time gaps in the figure are due to moderate drizzle. The time delay in forming fresh clouds after the drizzle may be noted.

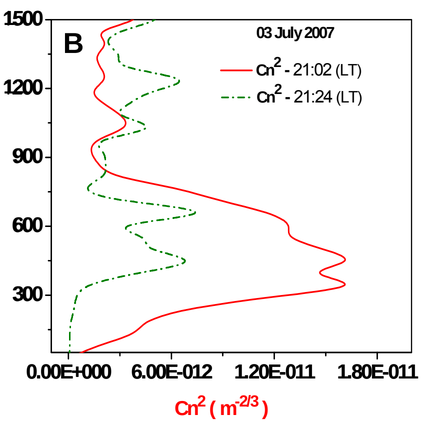
height region between 300 and 800 m while they were present simultaneously at two different levels, around 400 and 2000 m. Mapping of the 850 hPa wind field and total cloud cover from the NCEP / NCAR re-analysis data (Figure not shown) indicate west-southwesterly advection of marine air mass from the Arabian Sea onto the continent covering the experimental station is conducive for the formation of low-level clouds. It is further supported by the prevalence of total cloud cover of 90 % on 03 July and of 70 % on 06-07 June over the experimental site. It may be noted that there is subdued cloud activity immediately after the drizzle subsided, and there is a delay of about 20-30 minutes to revive the cloud activity. It implies that the existing CCN have already been either scavenged or removed and the atmosphere is to be 're-charged' with supply of fresh CCN. Moreover, the resurgence of cloud activity after certain delay hints the time required for aerosol contribution from the immediate cloud environment including the sub-cloud region.

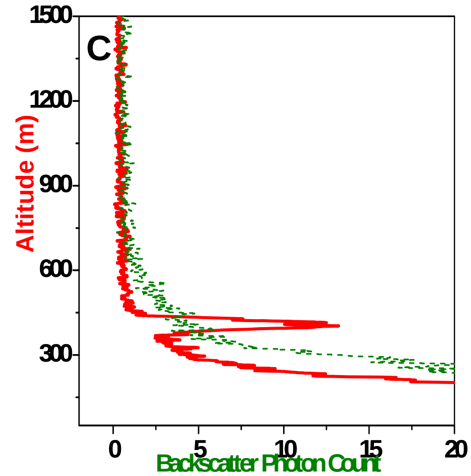
3.3 Turbulence Structures

One of the prominent mechanisms responsible for the maintenance of clouds is the vigorous turbulent mixing within the cloud column and the increased updraft velocity below the cloud-base. The strong updraft would help in the accumulation of moisture and condensation nuclei from the below-cloud region to the cloud-activation region. The occurrence of drizzle instigates heating just below the cloud-base through latent heat release, but cools the ground surface and in turn tends to stabilize the boundary layer [6]. Increased stability in the boundary layer would decrease the vertical updraft which in turn cuts down the supply of mass flux to the cloud region besides suppression of turbulence. The net effect of all these processes would results in negative feedback on the further growth of cloud, leading to dissipation of cloud cells. Turbulence within clouds is very common due to increased updrafts and downbursts. This turbulence is sensed by the electromagnetic lidar signals basically through fluctuations in the refractive index.

Propagation of an optical beam through a turbulent medium results in redistribution of the beam energy leading to intensity variations [7,8]. A measure of these fluctuations is made through a parameter called,







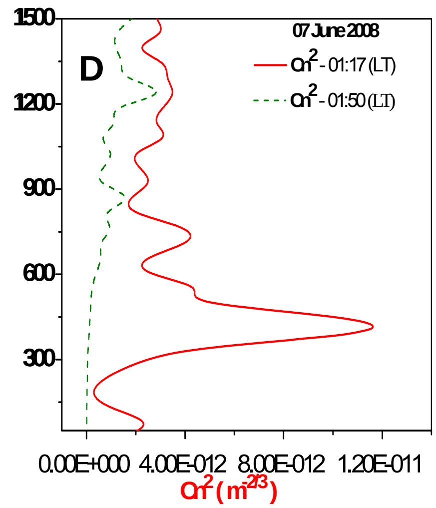


Figure 3. Lidar backscatter signatures from low-level cloud on (A) July 03, 2007 prior to (thick line) and after (thin dashed line) the drizzle event and (B) Vertical profiles of C_n^2 before and after the drizzle on 03 July 2007, (C) Backscatter strength of cloud echo between 400 m and 599 m before and after drizzle on June 07, 2008 and (D) corresponding C_n^2.

'refractive index structure parameter', denoted by C_n^2. By monitoring these intensity fluctuations, it is possible to compute the path-averaged optical C_n^2 as:

$$C_n^2 = 8.1\,\sigma_x^2\,K^{-7/6}\,L^{-11/6} \tag{1}$$

where σ_x is the log variance of amplitude fluctuations, K is the wave number (2π/λ, λ being the wavelength of operation) and L is the path-length of propagation. The higher values of C_n^2 indicate greater amplitude fluctuations of the signal which is induced by turbulence. This process is noticed through the weak turbulence observed after the occurrence of drizzle on 03 July 2007 and 07 June 2008.

From the data archived on 03 July 2007 and 07 June 2008, the path-averaged optical C_n^2 profiles were constructed prior to and subsequent to the occurrence of drizzle, and are shown plotted in Figure 3. The corresponding backscatter profiles are also plotted alongside the C_n^2 profiles in the figure. It can be seen from the figure that, on both occasions, prior to the drizzle event, there is increased cloudiness and correspondingly enhanced turbulence within the cloud cell. However, immediately after the drizzle, the turbulence got diminished by around an order of magnitude on 03 July and by many orders on 07 June, along with subdued cloud activity. The reduction in turbulence in the post-drizzle period, as already explained, may be due to the increased stability of the atmosphere attained through latent heat release by drizzle formation. Hence the cloud activity reduced both due to washout and chopping down of CCN supply by reduced updraft.

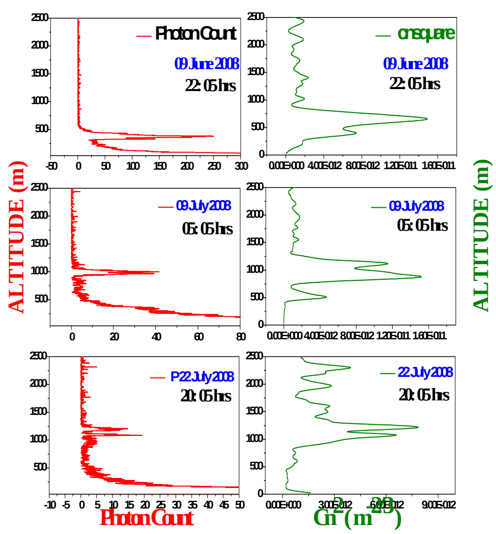


Figure 4. DPMPL-observed vertical profiles of cloud structure (left panels) and Cn^2, refractive index structure parameter which is a measure of atmospheric turbulence (right panels). Intense turbulence inside the cloud regions as compared to its out-side clear-air environment is evident from the figure.

Shown in Figure 4 are the vertical distributions of C_n^2, estimated from the lidar back-scatter intensity variations with height observed on some typical cloudy days over the experimental location. It is quite evident that intense turbulence inside the cloud as compared to the outside or cloud-free environment, which is consistent. It also reveals that turbulence increases with increase in cloud drop number density which is represented by the lidar cloud echo intensity.

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