IMPORTANCE OF RAMAN LIDAR AEROSOL EXTINCTION MEASUREMENTS FOR AEROSOL-CLOUD INTERACTION STUDIES

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ABSTRACT

Using a UV Raman Lidar for aerosol extinction, and combining Microwave Radiometer derived Liquid Water Path (LWP) with Multifilter Rotating Shadowband Radiometer derived Cloud Optical depth, to get cloud effective radius (R_{eff}), we observe under certain specialized conditions, clear signatures of the Twomey Aerosol Indirect effect on cloud droplet properties which are consistent with the theoretical bounds. We also show that the measurement is very sensitive to how far the aerosol layer is from the cloud base and demonstrate that surface PM25 is far less useful. Measurements from both the DOE ARM site and new results at CCNY are presented.

1. INTRODUCTION

One of the outstanding issues regarding the earth's energy balance and resultant forcing on the climate are the indirect effects that aerosols have on cloud radiative properties. In particular Twomey [1] described a mechanism in which increased aerosol loading results in higher concentration of cloud condensation nuclei which ultimately lead to increased cloud droplet number concentration and smaller effective cloud droplets which however have to be compared for constant liquid water paths. Unlike direct cloud effects on the climate, the aerosol-cloud indirect interactions are very hard to measure from satellites directly since simultaneous aerosol loadings (especially below cloud base) and cloud properties such as COD and/or Reff are not possible and therefore efforts at quantifying these effects are limited to statistical trend studied over large domains.

While such statistical studies have provided some useful information, poor temporal statistics makes it particularly difficult to establish underlying causal mechanisms. In addition, an equally difficult issue is to retrieve the true aerosol loading near the cloud base. In particular, it is quite evident that column measures of aerosol optical depth do not provide the vertical information needed to quantify the pollution level at the cloud base. Furthermore, the relationship between optical depth and particle number depends on the microphysical distribution models and does not discriminate between aerosol types below cloud base that impact cloud micro-physics and aerosol particles located higher than cloud top, that only interact with the radiative transfer above clouds. Therefore, it is clearly important to develop short term measurements with high temporal resolution to eliminate many of the above cited ambiguities. In particular, under such an approach, simultaneous measurements of clouds and aerosol loading below cloud base along with important vertical updraft data are achievable. Most important, within the measurement cycle, the exact nature of the cloud within the cloud lifecycle including general meso-scale processes is less important for these short term inter-cloud measurements.

Various efforts have been made to develop retrieval algorithms to infer COD and Reff from ground based passive radiometric measurements. In one approach, a Microwave

Radiometer (MWR) is combined with Millimetre-wavelength Cloud Radar (MMCR) to infer droplet diameters. In this case, the radar reflectivity and the MWR LWP provide the information to retrieve R_{eff}. However, the cost of the MMCR can be quite substantial. On the other hand, significant success in combining COD from the Multifilter Rotating Shadowband Radiometer (MFRSR) together with LWP from MWR is a reasonable cost-effective solution [2]. One drawback in this method is obviously the limitation that observations must be made during daytime. However, significant aerosol-cloud interaction signals should exist during daytime especially under conditions of strong convective heating which enhances vertical uptake. The relative simplicity and low cost of this method has motivated the deployment of such an approach at the CCNY

The main signature we wish to observe is the change in droplet effective radius (R_{eff}) as a function of aerosol loading. While a direct evaluation of aerosol number density is optimal, such a measurement is not realistic near cloud base. To this end, we make use of the conventional Raman Lidar technique to estimate aerosol extinction which is closely related to number density. In particular, to quantify the changes between droplets and aerosol loading, the Aerosol Cloud Index (ACI) was defined [3] as,

$$ACI = -\left(\frac{d(\log(R_{eff}))}{d(\log(\alpha))} \right) \quad (1)$$

which represents the relative change in mean cloud droplet effective radius (Reff) for a relative change in aerosol extinction, α_{ext} for clouds having the same LWP. It is useful to note that an upper theoretical limit of ACI < 1/3 exists.

2. METHODOLOGY

We make use of the methods described in [12]. Briefly, the MWR provides a direct retrieval of liquid water path (LWP) while the MFRSR measures the diffuse transmittance (T_{diff}). From these 2 measurements, we can simultaneously solve for cloud optical depth (τ_{cod}) and cloud droplet effective radius (R_{eff}) using the two independent relationships for LWP and T_{diff}

$$LWP(\tau_{cod}, R_{eff}) \approx \frac{2}{3}\tau_{cod}R_{eff} \quad (2)$$

$$T_{diff}(\tau_{cod}, R_{eff}) \quad (3)$$

The complexity of the measurements and the strict requirements to observe a meaningful Aerosol-Cloud signal severely limit the number of potential observations. The factors that must be accounted for include

1) Fine aerosol modes with angstrom coefficient with high Single Scattering Albedo (SSA). This allows us to restrict our cases to sulfate dominated aerosols
2) Low altitude water phase clouds with reasonably small Liquid Water path (50 < LWP < 90) to remove complications of mixed ice phase and maximize the observation of aerosol influence. In particular, higher LWP clouds will clearly be less affected by the aerosol fields.
3) Reasonably strong aerosol loadings to reduce the noise in the aerosol retrieval using the Raman Lidar approach
4) A significant vertical wind uptake which allows for a better mixing of the aerosol CCN's with the cloud LW. (use of HYSPLIT to insure vertical uptake)
5) Sufficiently homogeneous cloud decks that allow us to approximate the cloud diffuse radiance with a 1D radiative transfer model.

3. RESULTS

To explore the aerosol-cloud interaction and illustrate the need for a complete measurement testbed including lidar, we plot in figure 1, the Raman lidar derived extinction profile for a stable water phase cloud case from the ARM site [4].

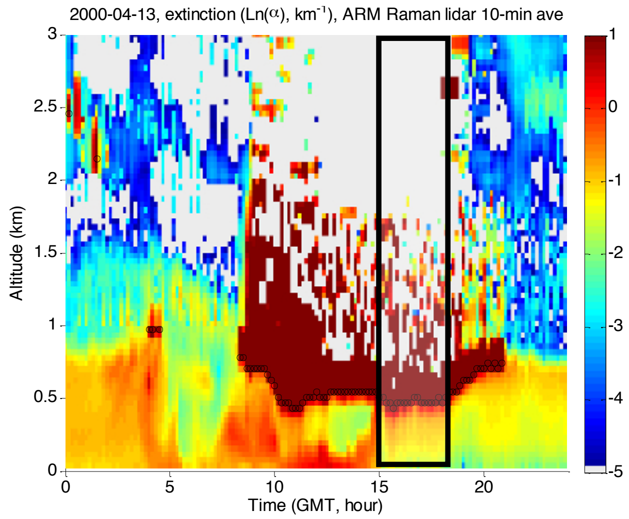

Fig. 1: Raman Lidar derived extinction profile and marked cloud boundary for April 13, 2000 at ARM SGP site

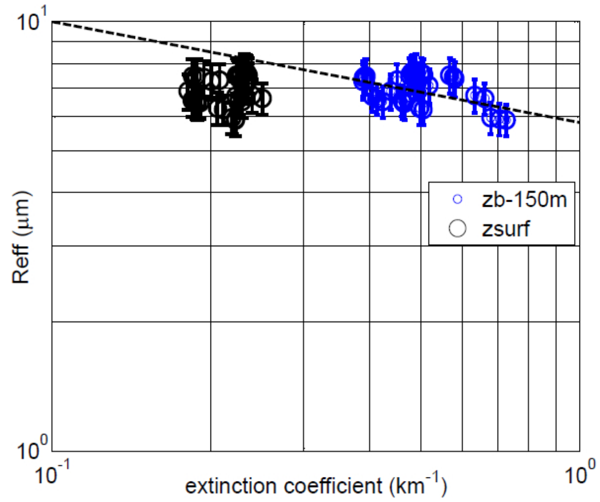

Fig. 2: Log-Log plot of -Raman lidar extinction below cloud against the cloud droplet effective radius. 'zb-150m' (blue circles) indicates the upper air atmospheric column layer which was used in the comparison (i.e 150 m below the cloud base altitude denoted by zb), while 'zsurf' refers to the atmospheric layer closest to the surface (~ 30m).

In figure 2, we show the relationship between the effective radius and aerosol extinction where we consider both the surface extinction (lidar ground bin = 30 m) as well as the extinction 150 m below the cloud base. Here the cloud base was determined using a simple extinction coefficient threshold of 1 m^{-1} and is displayed as black circles in figure 1. We note that the aloft aerosol measurement is critical in observing the AIE. In the example above, we have an ACI index of 0.18 which is reasonable based on the theoretical limits and other observational results.

The ARM site measurements motivated the deployment of a similar MFRSR / MWR / Raman Lidar testbed at CCNY in the hopes of being able to not only see AIE cases but to identify quantitative differences between them. However, as we pointed out in section 2, the difficulties in getting sufficient cases is the result of the strict conditions that a positive measurement must have. One interesting issue which we did not explore with the ARM site was the accuracy of the LWP measurement from the MWR. In order to explore this, we make use of 2 methods of calculating the LWP. 1) The NN approach which requires training at the local site 2) a simplified dual channel method [15].

In figure 3, we see that strong agreement occurs for all moderate LWP cases.

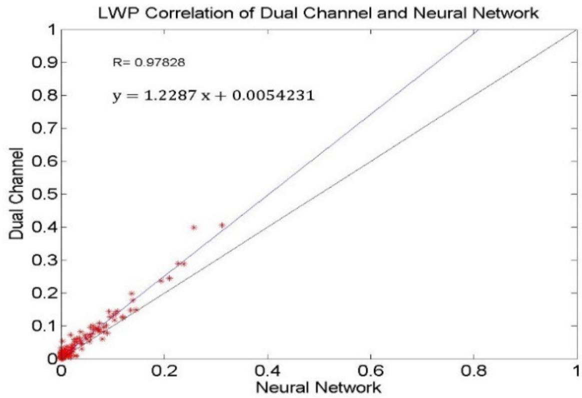

Fig. 3: Integrated liquid water path LWP (mm) correlation between two methods

We applied both the DC and NN method to a case where all conditions were met. (Other cases will be presented at the conference). The results are shown in figure 4. The main observation is that the DC method actually allows for more retrievals without any degradation. In fact, the larger number of retrievals allows improved regression analysis in this case. In addition, the ACI magnitude is very comparable between the 2 methods. In addition, this example, just like the ARM site

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demonstrates that the results degrade if we use aerosol layers too far below the cloud. In fact, strong degradation of the ACI signal occurs if we are further than 300 meters below cloud base (not shown here).

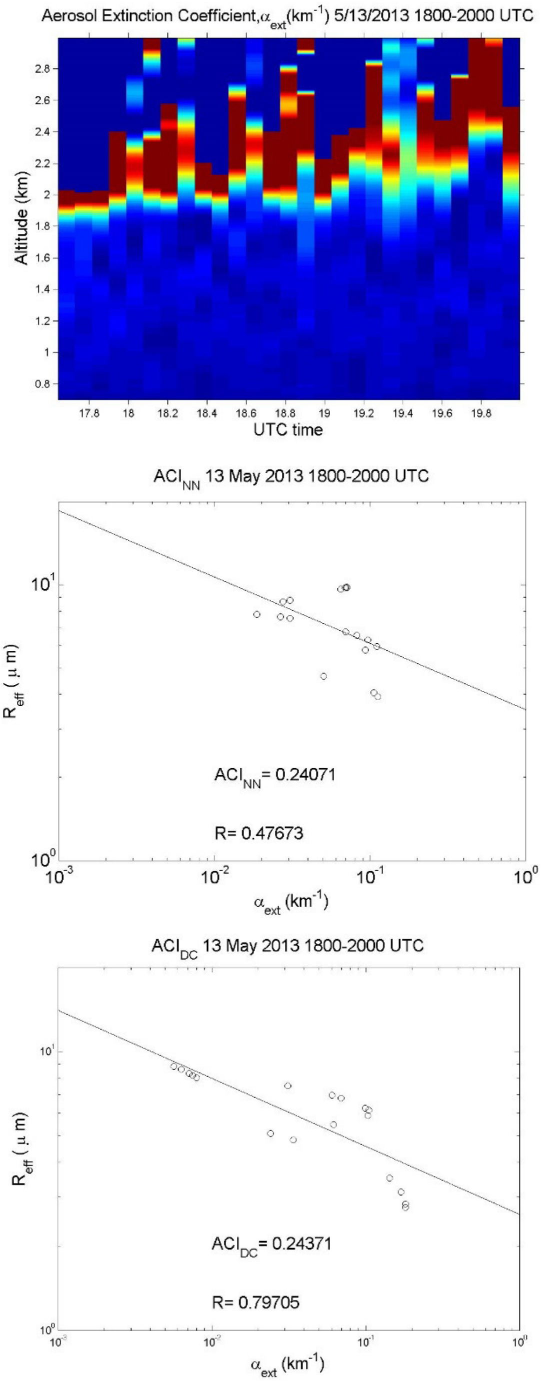

Fig. 4: Example of ACI for CCNY system. a) 3D lidar image b) ACI using NN c) using DC

4. CONCLUSIONS

We have made a preliminary investigation of the potential of quantifying and generally observing Aerosol Cloud Interactions at both the DOE ARM site and CCNY. We have demonstrated that accurate ACI measurements require LIDAR observations that can probe the aerosol loading sufficiently near cloud base. We also note (not shown here) that using surface $PM_{2.5}$ mass as a proxy for particle number.

In addition, to provide some internal consistency checks, we use 2 different MWR retrieval approaches and show good consistency between the methods. In addition, we will present matchups with MODIS cloud retrievals that demonstrate the general soundness of the ground based approach.

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