

Vertical Profiles of Cloud Extinction and Cloud Top Droplet Number Concentration in Warm Clouds Derived from Airborne Lidar and Polarimeter Measurements

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Abstract: NASA Langley Research Center airborne second generation High Spectral Resolution Lidar (HSRL-2) participated in a multiyear (2020-2022) NASA field campaign over the North Atlantic Ocean that studied aerosol-cloud interactions using two coordinated aircraft. One aircraft deployed *in situ* instruments and flew above, within, and below shallow marine clouds while another aircraft followed the same ground tracks and deployed two remote sensing instruments that sampled near the cloud top. The remote sensing instruments were the HSRL-2 and the Goddard Institute for Space Studies Research Center's Scanning Polarimeter (RSP). The lidar provided profiles of cloud top extinction and average lidar ratios to within 2.5 optical depths into the cloud, and the polarimeter provided size distribution parameters derived from the cloud bow region of the scattering phase function. The measurements are then combined to derive the cloud top droplet number density, N_d . Here we present data products from both the lidar and polarimeter and compare N_d derived from the remote sensing and *in situ* measurements.

1. Introduction

Aircraft flights conducted over the western North Atlantic Ocean during the winter and summer over three years provide extensive measurements of low-level water clouds and mixed phase clouds that include a wide range of cloud size distributions and number densities.

We present a retrieval method that takes advantage of the High Spectral Resolution Lidar (HSRL) technique and high (1.25m) vertical sampling to derive profiles of extinction from cloud top down to ~ 2.5 optical depths into the cloud. This technique uses depolarization relations to correct for the cloud multiple scattering [1,2].

In addition, the combination of simultaneous and collocated airborne HSRL and RSP measurements permits retrievals of cloud droplet number concentrations (N_d).

Specifically, this abstract focuses on evaluating:

1) cloud top extinction derived from the NASA LaRC 2nd Generation High Spectral Resolution Lidar (HSRL-2) measurements.

2) cloud droplet number density (N_d) derived from the HSRL-2 retrievals of cloud extinction and the RSP retrievals of cloud drop size distribution parameters.

2. Instrument Description

The NASA Langley HSRL-2 instrument was recently upgraded to sample the ocean subsurface and cloud tops at high vertical resolution (1.25 m in air or 120MHz). The HSRL-2 instrument employs the HSRL technique at both 355nm and 532nm and uses the standard backscatter technique at 1064nm. Details of the first generation HSRL-1 system are provided by [3] and the implementation of the 355 nm measurements is described in [4].

For this presentation, only the HSRL measurements at 532nm are used.

3. Methodology

The HSRL-1 and second generation HSRL-2 instruments provide high resolution measurements within highly attenuating warm clouds. The high vertical resolution and the capability to retrieve the optical depth from the lidar to the cloud top using the HSRL technique provide a quantitative approach to sampling cloud top extinction in opaque warm clouds. The extinction retrieval in warm clouds employs the seminal empirical relationship developed by Hu et al. [1] relating the single-to-total integrated attenuated backscatter using the integrated depolarization ratio. Moreover, Roy et al. [3] have shown that this relationship developed in [1] is valid over the range from the cloud top (or bottom depending on orientation of the lidar) and therefore a profile of the attenuation can be determined if there is sufficient resolution in the lidar measurements. The method presented implements the following retrieval steps: 1) determine if a lidar profile contains a cloud and use the surface return to determine if it opaque (i.e. $T \sim 0$), 2) for opaque clouds the average lidar ratio can be determined from the total integrated attenuated backscatter (IAB) and the total lidar integrated depolarization (LID) that accounts for the multiple scattering when integrating through the cloud (i.e. the asymptote values) based on [1,2], 3) then assuming the lidar ratio is constant near cloud top, derive the transmission into the cloud as a function of range using the IAB and LID from the cloud top to the specific range within the cloud, 4) lastly from the single scattering transmission profile the extinction profile is calculated from difference in the transmission at each range. For the airborne HSRL-2 instrument, this results in robust retrievals into the cloud up to 2.5 optical depths (~50-100 m) with a resolution of ~3.75 m. Note that the transmission from the lidar to the cloud top is also required. Therefore, the attenuated backscatter is normalized at the cloud top using the total attenuation determined by the established HSRL technique.

The polarimeter, RSP, uses the view angle dependence of the polarized reflectance in the rainbow ('cloudbow') region to derive the cloud drop effective radius (R_{eff}) and effective variance (V_{eff}) of the size distribution; these

retrievals have been validated with airborne *in situ* cloud probe measurements [6]. Note that the polarized reflectance is dominated by single scattering from cloud particles and less sensitive to multiple scattering, 3D effects, and aerosol scattering. The retrievals using the Rainbow Fourier Transform [6] do not assume a size distribution and can provide effective radii and variances for different modes. Here, the median effective radius and variance values are used to calculate an average scattering cross section of the cloud particles.

The cloud top droplet number concentration can be directly calculated by dividing the average extinction derived from the lidar data by the scattering cross section which is calculated from the polarimeter size parameters as shown below.

$$N_d = \frac{\text{Extinction}}{\text{Scattering Cross Section}}$$

For the results presented, the average extinction from 0.1 to 1 optical depth into the cloud top is used to match the expected weighting of the polarimeter measurements.

4. Measurements

The Aerosol Cloud meTeorology Interactions oVer the western ATlantic Experiement (ACTIVATE) took place during 2020-2022 and sampled various shallow marine clouds in the Western North Atlantic Ocean east of the United States [7]. The flights consisted of coordinated sampling by two research aircraft; one aircraft flew at high altitude (~9km) and deployed HSRL-2 and RSP while the second aircraft flew directly below at low altitude (~<3km) and conducted *in situ* aerosol, cloud and trace gas phase measurements. Cloud measurements were acquired by a standard suite of wing-mounted cloud probes [8]. These coordinated flights provide a unique dataset to use coincident *in situ* cloud measurements to evaluate the lidar remote sensing retrievals of extinction and N_d derived from the combined lidar and polarimeter datasets.

A case study from 5 May 2022 is discussed here. Figure 1 shows a segment of the data where the *in situ* aircraft sampled near the cloud top. The aircraft altitude and cloud top heights derived from the lidar are shown in the bottom panel. The shaded regions in the panels show where the *in situ* aircraft within one optical

depth of the cloud top. The *in situ* measurements here having been spatially collocated to match the remote sampling location even though they could be collected at slightly different times. The lidar retrievals of cloud extinction and lidar+polarimeter retrievals of N_d are generally in agreement within the corresponding values derived from the *in situ* measurements and show similar trends. It is recognized that the *in situ* data also have significant differences for N_d over this segment, yet corrections for coincidence effects have not been applied to the various instruments.

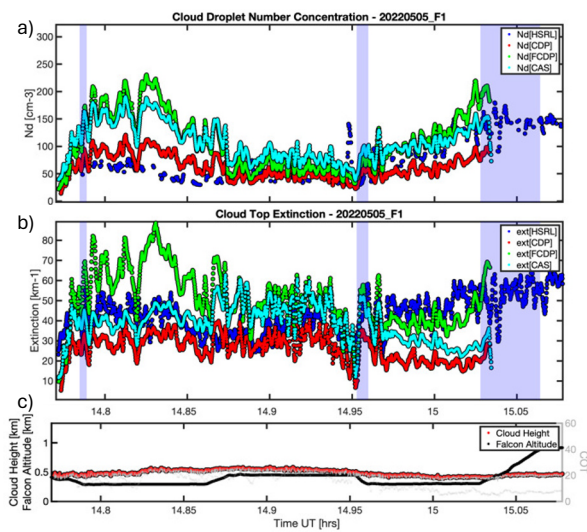


Figure 1. Time series plot over ~15 min from the three different wing probes and the lidar and polarimeter of: a) N_d , b) extinction, c) cloud top height (red) from lidar and the *in situ* aircraft altitude (black). The blue shading highlights time when probes sampled within one optical depth of cloud top.

Both the extinction and the effective radius and variance of the droplet size distribution will vary significantly with height within the cloud profile. Figure 2 shows one example of the extinction profile near 15 UT (the last shaded region) when the *in situ* aircraft profiled through the cloud top. Magenta data points were collected at 0.5 sec intervals within the ~3mins time window spatially coincident with the *in situ* a/c ramp, and the blue line represents the mean profile above cloud top during that time. The offset distance (time) between aircraft is 58 m (1.7 mins). Note that the cloud top height changes over the sampling interval with a standard deviation of 20 m. This figure shows similar values derived from measurements from

two of the wing probes (CDP – Cloud Droplet Probe and CAS – Cloud Aerosol Spectrometer) with higher values measured from the FCDP (Fast Cloud Droplet Probe). The vertical profiles follow similar trends providing confidence in the lidar retrievals of the extinction profile.

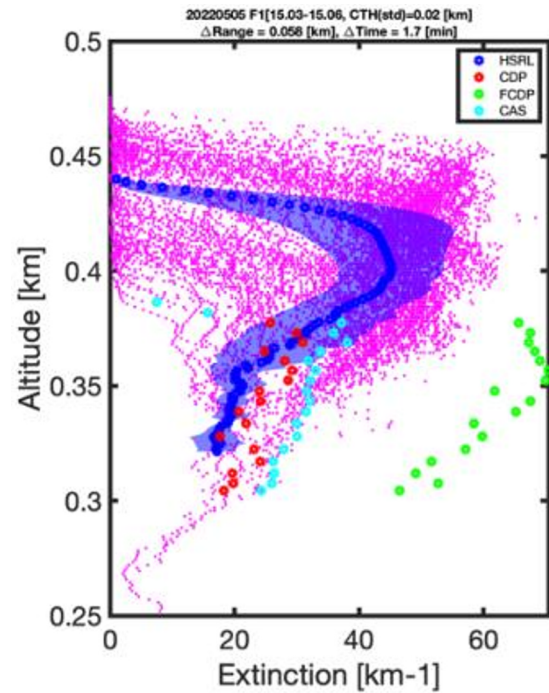


Figure 2. Spatially matched profiles of extinction near cloud top, where magenta is the individual profiles (0.5 s average) along the sampling period, the blue is the median and is shaded with the standard deviation. The red, green, and cyan points are the measurements from three different wing probes.

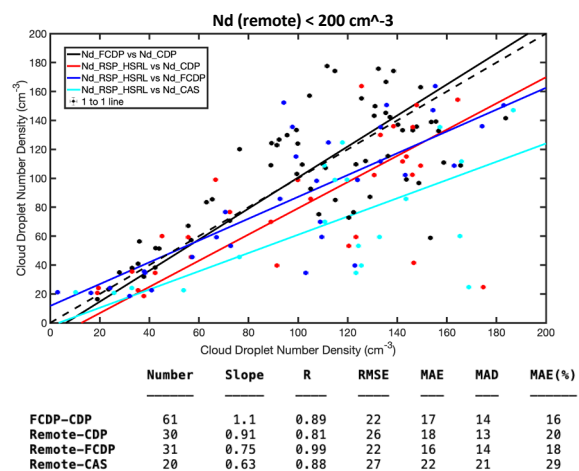


Figure 3. Comparison of N_d measurements from the lidar+polarimeter (ordinate) to the wing probes (abscissa) over the entire

ACTIVATE dataset. N_d is limited to less than 200 cm^{-3} .

Lastly, N_d was computed from the combined lidar and polarimeter data for all ACTIVATE flights near cloud top and compared with the corresponding values derived from the spatially matched wing probe data where the N_d was less than 200 cm^{-3} .

These comparisons are shown in Figure 3 along with the statistics that show mean absolute deviations in N_d of 20-30% and correlation coefficients ranging from 0.8-1 amongst the different probes. Comparisons were limited to N_d less than 200 cm^{-3} as higher droplet concentrations were observed in variable conditions, such as post frontal clouds, that are challenging to match both spatially and temporally. Further analysis is required to understand these very high droplet number concentration cases.

5. Summary

Data from two remote sensors, HSRL-2 and RSP, were combined to derive cloud drop number density N_d . These retrievals of N_d generally compare well with corresponding values derived from coincident measurements from airborne *in situ* measurements when limited to number concentrations less than 200 cm^{-3} .

The lidar-derived cloud extinction profiles show better agreement with corresponding profiles derived from the coincident *in situ* wing-probe CDP and CAS measurements than extinction profiles derived using the FCDP measurements. Note that there were large temporal and spatial variabilities in the cloud parameters near cloud top, which makes detailed assessments challenging. However, evaluating these comparisons start to build confidence in the lidar cloud extinction retrievals.

The combined lidar and polarimeter retrievals of N_d provide valuable additional insight to study small-scale variability in cloud properties near the cloud top. Although not shown, the spatial trends in cloud extinction and N_d derived from the lidar and polarimeter measurements from both winter and summer flights are consistent with similar trends derived from the *in situ* cloud probe measurements.

6. References

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