Evaluating Combined Lidar and Polarimeter Measurements of Cloud Top Parameters

(Extinction, Scattering Cross Sections, and Droplet Number Density, Liquid Water Content)

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Introduction and Objectives

Aircraft flights conducted during the ACTIVATE field campaigns (2020-2022) provided an opportunity to collect an extensive dataset sampling low-level water clouds and mixed phase clouds which had a wide range of cloud size distributions and number densities over different seasons.

We present a new method taking 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 takes advantage the depolarization relations developed by Yongxiang Hu in 2007 to correct for the multiple scattering. The airborne HSRL was flown with the Research Scanning Polarimeter in two seasons over three year (2020-2022) during NASA's ACTIVATE campaign focused on the Western North Atlantic Ocean region.

Specifically, this analysis focuses on the following:

1) Evaluating the lidar cloud top extinction data product from the NASA LaRC 2nd Generation High Spectral Resolution Lidar (HSRL-2) instrument.

2) Evaluating the combined lidar and polarimeter retrievals from the NASA GISS Research Scanning Polarimeter (RSP) of the cloud droplet number density (N_d) derived from the lidar extinction and the polarimeter size distribution parameters.

In situ data are used to compare these retrievals during case study flights.

Instruments

Two advanced remote sensing instruments

- Research Scanning Polarimeter (RSP – Brian Cairns)
- High Spectral Resolution Lidar (HSRL – Chris Hostetler)

Co-located in situ sampling of clouds microphysics

- Langley Aerosol Group Experiment Cloud Probes (CDP/CAS –Richard Moore)
- DLR Cloud Probes – (FCDP/2DS – Christiane Voigt, Simon)

Methodology: Extinction Profile Retrieval

High Spectral Resolution Lidar (HSRL-2 – NASA LaRC)

Derive lidar ratio for opaque liquid water clouds using the multiple scattering relationship from Hu et al., 2006 which is determined from the integrated attenuated backscatter and depolarization ratio. There are two methods to derive the extinction. Following the relationship derived by Hu et al., the accumulated single-to-total scattering factor, A_s is defined below and used in both methods. Note that it is range dependent (Cao and Roy, 2010).

Hu et al., 2006, 2007

Slope method

Pros
- Calibration is not required to determine slope.
- Provides information further into the cloud (>2.5 optical depths)

Cons
- Requires assumption of both constant lidar ratio & backscatter within cloud
- Requires calibration down to cloud top to determine lidar ratio
- Requires single-multiple scattering to be constant

Profile method (Operationally using airborne HSRL)

Pros
- Does not require assumption of constant backscatter.
- Provides information near the cloud top (<~2.5 optical depths within cloud)

Cons
- Requires assumption of constant lidar ratio within cloud
- Requires calibration down to cloud top

Equations

$\gamma_S \equiv single\ scattering\ integreated\ attenuated\ backscatter$

$$Equation\ 1{:}\ \gamma_S = \frac{1}{2S_p}\left(1 - T_P^2\left(r_{top}, r\right)\right)$$

$\gamma_T \equiv$ total, including multiple $scattering, integreated\ attenuated\ backscatter$

$$Equation\ 2{:}\ \gamma_T = \frac{1}{2S_p A_S(r)}\left(1 - T_P^2\left(r_{top}, r\right)\right)$$

$A_S(r) \equiv single\ to\ total\ integrated\ attenuated\ backscatter$

$\delta(r) \equiv integrated\ depolarization\ ratio$

$$Equation\ 3{:}\ A_S(r) \equiv \frac{\gamma_S(r)}{\gamma_T(r)} = \left(\frac{1-\delta(r)}{1+\delta(r)}\right)^2$$

$Solve\ for$ lidar ratio $from$ Eqn 2 & 3 at range where $T_P^2 = 0\ (opaque\ cloud)$

Lidar Ratio

$$S_p = \frac{1}{2A_S(r)\gamma_T(r)}$$

$Solve\ for\ the\ transmission$ and extinction $from\ equations\ above$

$$T_P\left(r_{top}, r\right) = \sqrt{1 - 2A_s(r)\gamma_T(r)S_p}$$

Extinction Profile

$$\alpha(r) = \frac{d}{dr}\left[T_P\left(r_{top}, r\right)\right]$$

Research Scanning Polarimeter (RSP - NASA GISS)

Products: effective radius and variance of cloud drop size distribution and cross section

- Uses the view angle dependence of polarized reflectance in the rainbow ('cloudbow') region to derive the cloud top drop size parameters (Reff, Veff)
- 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 do not assume a size distribution and can provide different effective radii and variances in different modes. Here, the median effective radius and variance values are used.

Alexandrov, et al. *2012*

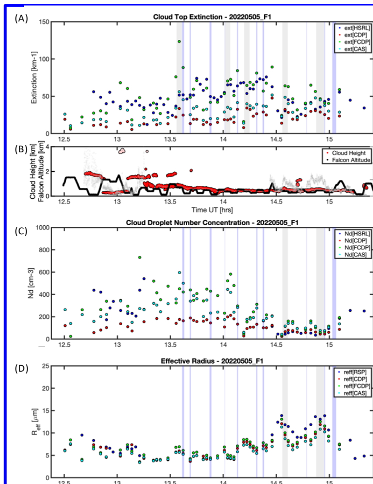
Cloud Droplet Number Concentration

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

From lidar (HSRL) extinction retrieval with multiple scattering correction

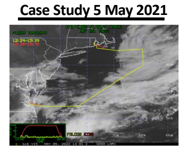
From polarimeter (RSP) size distributions

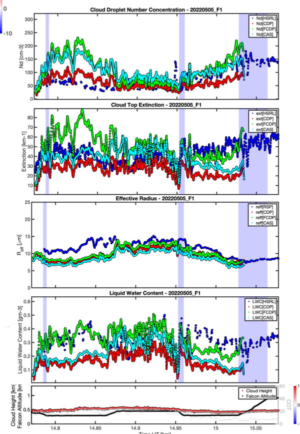
Case Study 5 May 2021



(A) Leg Average comparisons of HSRL extinction with calculated extinction from cloud probes.
(B) Cloud top heights from HSRL with cloud top temperatures color coded from -10 to 10 C showing warm cloud tops. The insitu data is collocated in time to the remote sensing data and the altitude is shown with black line (Falcon Altitude). For this flight, the Cloud Optical Thickness (COT) is plotted in gray.
(C) Leg average comparisons of combined (RSP and HSRL) cloud droplet number density (Nd). Note that RSP did not have RFT retrievals during the middle portion of this flight due to the sun angles.
(D) Leg average effective radius (RSP) compared to the insitu probes.
Note: the gray shading shows below cloud top legs where data products would better agree. Also, blue shading regions show the ascents and descents that were used to compare profiles of extinction.

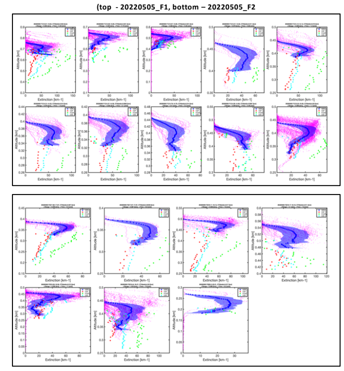
- The remote measurements capture the decrease in Nd near the end of the flight with values (<100) on the eastern portion of the flight.
- For the leg average extinction, there is significant differences in the three different probes. In addition, the HSRL derived product is an average from 0.1-1 optical depths into the cloud. It is noted that there is a significant change in the extinction with depth into the clouds.
- The changes in effective radius matches well during the flight and shows a similar trend with peak values near 14μm.





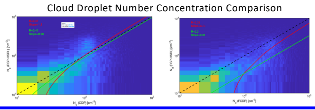
Subsection of flight 1 (F1) showing Nd, Extinction (averaged over 0.1-1 OD), Reff, and LWC that matches the last three vertical profiles. The blue shading is the time that the profiles are compared. Note for the first profile (~14.7UT) the CDP matches better than the other two probes and for the last profile the CAS is consistent with remote sensor values.

Comparison of Wing Probes and Average Profile from HSRL (top - 20220505_F1, bottom – 20220505_F2

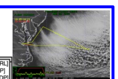


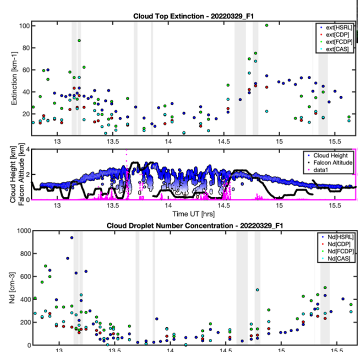
- The profile data provides a different perspective in comparing to the wing probes and highlights the variability with distance along track and with depth into the cloud. In addition, it highlights changes with cloud top height.
- The CDP and CAS compare within the variability of the remote sensor data for most profiles. The FCDP is higher than the other probes during these comparisons. This is similar for other flights in 2022.
- The differences in the probe data limits assessing the uncertainty of the cloud top extinction profiles and highlight the challenges in comparing to the remote sensing extinction data.
- Other challenges are due to the change in cloud height along the track where each profile is a 0.5 second interval (50-75m) and the temporal and spatial match-up times.
- The blue line (shading) is the mean profile averaged (standard deviation) from cloud top on each profile during the ramp.
- Magenta lines show all profiles within the time window (~0.5-3mins) over the same spatial region that the wing probes sampled during ramps.
- The offset in distance and time is also provided for each comparison. Also, the standard deviation of the cloud top is provided to estimate the variations in the cloud vertical structure.

Cloud Droplet Number Concentration Comparison



Case Study 29 March 2022

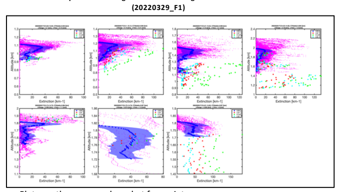




Top: Leg Average comparisons of HSRL extinction with calculated extinction from cloud probes.
Bottom: Leg average comparisons of combined (RSP and HSRL) cloud droplet number density (Nd)
Middle: Cloud top heights from HSRL with cloud top temperatures color coded from -10 to 10 C. The insitu data is collocated time to the remote sensing data and the altitude is shown with black line (Falcon Altitude). For this flight, the ice number density (2DS) is plotted in magenta.

The remote sensors capture the general trend of Nd along the post frontal clouds with larger (200-600 cm-3) values near the cost and smaller values (<100) on the eastern portion of the flight.

Comparison of Wing Probes and Average Profile from HSRL (20220329_F1)



- Plots are the same as above but for a winter case.
- The second flight on 20220329 had limited comparison profiles.
- The CDP and CAS data matched best to the lidar profiles during the ramps on this flight with the FCDP being higher for this flight with the best temporal and spatial coordination (2nd plot on top row).

Lidar Ratios

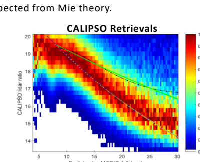
What is it?

- Lidar Ratio: S_c= extinction/backscatter (180 degree)

Why would we care about it?

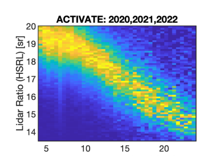
- Does not depend on number concentration, therefore it is an intensive parameter that provides information on the microphysics of the cloud (varies with effective radius).
- The lidar ratio is a function of the particle size distribution (RSP retrievals) and the index of refraction and can be calculated from Lorenz-Mie Theory.
- Can be directly compared to retrievals of the size distributions calculated from RSP and insitu wing probes.
- Range of lidar ratios from ACTIVATE are consistent with CALIPSO retrievals and extend to lower values than expected from Mie theory.

CALIPSO Retrievals



Courtesy of Yong Hu, unpublished.

ACTIVATE: 2020,2021,2022



Summary

- Archived cloud products from HSRL. Combined remote sensor data (RSP & HSRL) to calculate Nd and LWC. Created merge files with remote sensing data and wing probe data (FCDP, CDP, CAS).
- Comparison of N_d compare well with the CDP when limited to number concentrations less than 100 with a slope of 0.96 and a correlation coefficient of 0.4 when comparing all altitudes. The slope for the FCDP is 0.8 when fit with concentrations less than 1000 and 0.3 when limited to values less than 100.
- Comparisons of the wing probe to the extinction profiles are shown for two flights during 2022 (winter and summer) showing better agreement with the CDP and CAS than the FCDP. However, we are still assessing best method to evaluate extinction. Variability of the extinction at cloud top, changes in the cloud top height, and with large differences in the cloud probes make quantitative assessments challenging. *LWC from the WCM probe might be helpful in assessing the cloud performance*.
- For the ACTIVATE campaign, there is significant changes in the cloud top extinction and the lidar along with the polarimeter can provides insight into how the microphysical properties are changing along track and with depth into the cloud.
- The spatial trends from both the winter and summer flights are consistent with changes measured by the wing probes for both the extinction (averaged from 0.1-1 OD) and N_d from the combined remote sensors.
- Lidar ratios are consistent with those retrieved from CALIPSO and vary more than expected from Mie theory.

References

1. Hu, Yongxiang, et al. "Simple relation between lidar multiple scattering and depolarization for water clouds." *Optics letters* 31.12 (2006): 1809-1811.
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3. Roy, Gilles, and Xiaoying Cao. "Inversion of water cloud lidar signals based on accumulated depolarization ratio." *Applied optics* 49.9 (2010): 1630-1635.
4. Alexandrov, Mikhail D., et al. "Accuracy assessments of cloud droplet size retrievals from polarized reflectance measurements by the research scanning polarimeter." *Remote Sensing of Environment* 125 (2012): 92-111.