LIDAR-BASED RETRIEVALS OF THE MICROPHYSICAL PROPERTIES OF MIXED-PHASE ARCTIC STRATUS CLOUDS AND PRECIPITATION

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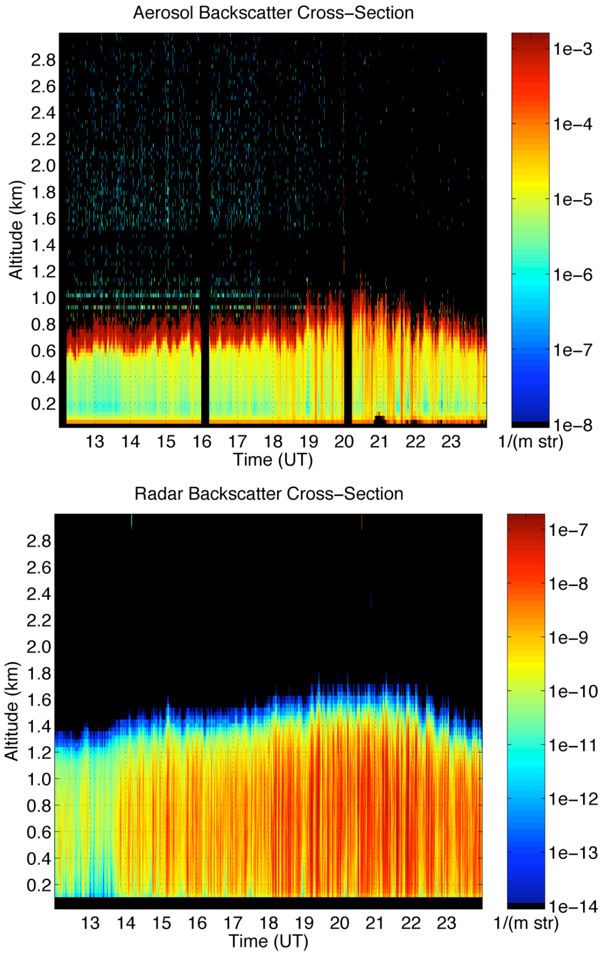
ABSTRACT

The University of Wisconsin Arctic High Spectral Resolution Lidar has acquired months of continuous measurements in two high Arctic locations. These measurements have been combined with those taken by a NOAA ETL Millimeter Cloud Radar to establish a long-range data set of cloud microphysical property retrievals. These properties include effective particle size, number density and water content. Examples from this data set for Arctic stratus are reviewed here, along with the methodology used in the retrievals.

1. INTRODUCTION

The University of Wisconsin Arctic High Spectral Resolution Lidar (AHSRL, Eloranta) has been deployed to two Arctic locations for extended measurement campaigns. The first of these was a 55-day campaign in Barrow, Alaska as part of the Mixed-Phase Arctic Clouds Experiment (M-PACE, Harrington and Verlinde, 2004) during the fall of 2004. The second and current deployment location is Eureka, Canada, where the system has been operating since August of 2005.

In both Barrow and Eureka, mixed-phase boundary layer Arctic stratus have been detected. These cloud structures have proven to be very difficult for the modeling community to simulate. Because the presence of both liquid and ice, the simulations tend to be very sensitive to the relative quantities of each phase. When too much ice is present, the cloud glaciates, and when not enough is present, the amount of liquid in the cloud increases without bound. The difference between these two states in terms of the radiative budget is of course very large, and therefore, accurate representation of these clouds in climate models becomes imperative to accurate future climate prediction. Therefore, ongoing projects throughout the modeling community are aimed at increasing the ability of simulations to capture the cloud state properly. Retrievals achieved using the AHSRL and the MMCR are presented as a source of validation for these simulations, as well as a source of additional insight into the processes governing these complex cloud structures.


Aerosol Backscatter Cross–Section

Radar Backscatter Cross–Section

Fig. 1. AHSRL aerosol backscatter cross-section (top) and MMCR backscatter cross-section (bottom) for 9 October 2004.

The retrieval algorithms used are very similar to those used by Donnovan and Van Lammeren (2001). From the lidar and radar backscatter cross-section, particle effective size, particle number density and water content are derived. In addition, for Arctic stratus cases, the return signal of both instruments is separated into that resulting from liquid and that resulting from ice. This separation is used to gain increased understanding of the interaction and radiative effects of both phases with time. Unlike with previous applications of this retrieval technique, a priori assumptions are not used to correct for attenuation. This is because the AHSRL is able to provide absolutely calibrated measurements of scattering cross-section. This is a significant advance in the use of this retrieval technique because results are heavily dependent upon correct backscatter cross-section measurement.

Validation of retrievals is done for M-PACE cases for which the University of North Dakota Citation aircraft was recording in-situ microphysical measurements near the Barrow lidar site. The October 9 case (fig. 1) is featured here.

2. MICROPHYSICAL RETRIEVALS

Retrieval methods are derived mainly from Donnovan and Van Lammeren (2001), and are reviewed here for reference.

2.1 Effective radius

For a distribution of particles, the radar scattering cross-section is equal to:

$$\beta_{rad} = \frac{24\pi^3 k^2}{\lambda^4}\left\langle V^2 \right\rangle \tag{1}$$

where k^2 is the dielectric constant, λ the radar wavelength, and $\left\langle V^2 \right\rangle$ the average volume squared. The lidar scattering cross-section is equal to:

$$\beta_{lid} = 2\left\langle A \right\rangle \tag{2}$$

where $\left\langle A \right\rangle$ is the average area of the particle distribution.

Using a backscatter phase function for both signals, backscatter cross-sections can be used in a ratio to come up with this expression:

$$\frac{\frac{P(180)}{4\pi}}{\frac{3}{8\pi}} \frac{\beta'_{rad}}{\beta'_{lid}} = \frac{12\pi^3 k^2}{\lambda^4} \frac{\left\langle V^2 \right\rangle}{\left\langle A \right\rangle} \tag{3}$$

where β' is now the backscatter cross-section. Using the definition for effective radius:

$$r_{eff} = \frac{\pi}{\frac{4}{3}\pi} \frac{\left\langle V \right\rangle}{\left\langle A \right\rangle} \tag{4}$$

equation (3) becomes:

$$\frac{\frac{P(180)}{4\pi}}{\frac{3}{8\pi}} \frac{\beta'_{rad}}{\beta'_{lid}} = \frac{16\pi^3 k^2}{\lambda^4} r_{eff} \frac{\left\langle V^2 \right\rangle}{\left\langle V \right\rangle} \tag{5}$$

This expression can be solved for effective radius, assuming an expression for the volume of a particle and integrating over a distribution. In this study, a modified gamma distribution was utilized, and the volume of a particle is defined as:

$$V = \sigma_V \frac{\pi}{6} D_{ref}^{3-\delta_V} D^{\delta_V} \tag{6}$$

where σ_V and δ_V are user supplied parameters, and are equal to 1 and 3 respectively for water.

2.2 Number Density

The amount of particles in the scattering volume is related to the backscatter cross-section as follows:

$$N = \frac{\beta'_{lid}}{2\left(\frac{P(180)}{4\pi}\right)\left\langle A \right\rangle} \tag{7}$$

2.3 Water content

Having an estimate for the number of particles and their size allows for an estimate of water content:

$$WC = \frac{2}{3} D_{eff} \left\langle A \right\rangle N \rho_{ice} \tag{8}$$

2.4 Phase separation for stratus cases

For the Arctic stratus cases, an attempt was made to separate liquid and ice portions of the retrieval. In order to accomplish this, measured backscatter cross section directly below cloud base level is assumed to be equal to the ice contribution inside the cloud at that time. This is done since precipitation falling from the cloud is known to be predominantly ice. This contribution is then subtracted out of the cloud to determine the portion of the signal resulting from liquid. The liquid portion then can be subtracted from the total return to determine an ice-only backscatter cross-section. This separation is calculated in order to better understand how much of the water content is due to each phase. Since the radar signal is strongly connected to the amount of ice present, and the lidar signal is more dependent upon the amount of water inside the scattering volume, both measurements must be analyzed to attain information on relative quantities of each phase.

3. RETRIEVAL EXAMPLES

Examples shown here are for the 9th of October 2004. The Atmospheric Radiation Measurement (ARM) Cloud Parameterization and Modeling Workgroup is using this date as one of many test cases to improve model handling of mixed phase stratus. Retrievals shown here are for ice and water phases combined, with ice volume being equal to 1/5 that of a sphere of the effective diameter.

The top of fig. 2 shows a time-height cross-section of the effective radius retrieval. The area along the top of the retrieval area (~600-1000 m) is the cloud, and the area below it is precipitation. Depolarization measurements taken with the lidar reveal that the precipitation is ice, while the cloud contains a significant amount of liquid droplets. Here, sizes seem to agree with that conclusion, with very small particles (cloud droplets) inside the cloud region, and larger particles falling from the cloud.

The center portion of fig. 2 shows a similar cross-section for number density. Once again, this makes physical sense, with a large number of particles inside the cloud, and a significantly reduced amount in the sub-cloud region. Ground observations from Barrow reveal very light snowfall, so values around 2-3 per liter are not surprising.

The bottom of fig. 2 illustrates the water content retrieval. High water content in-cloud is prevalent the first few hours of observation. Towards the end of the observation period, there are heavier bursts of precipitation, sometimes causing significant enough attenuation to hide the cloud, and therefore the cloud water content appears to be reduced towards the end of the period.

4. VALIDATION

The University of North Dakota Citation aircraft was present during M-PACE and in-situ measurements from that platform are utilized to validate values from the radar-lidar retrieval.

Figure 3 shows examples of comparisons between lidar-radar retrieval profiles with those of in-situ measurements. The top image compares effective radius retrievals with measurements taken using the Forward Scattering Spectrometer Probe (FSSP, nominal diameter range: 1-55 μm) and one-dimensional cloud probe (1DC, nominal diameter range: 20-120 μm).

Retrieval values seem to be comparable to 1DC measurements below cloud height (~500-600 m), as would be expected. Once at cloud altitudes, retrieval values fall in between the FSSP and the 1DC. This is consistent with expectations for a mixed-phase situation.

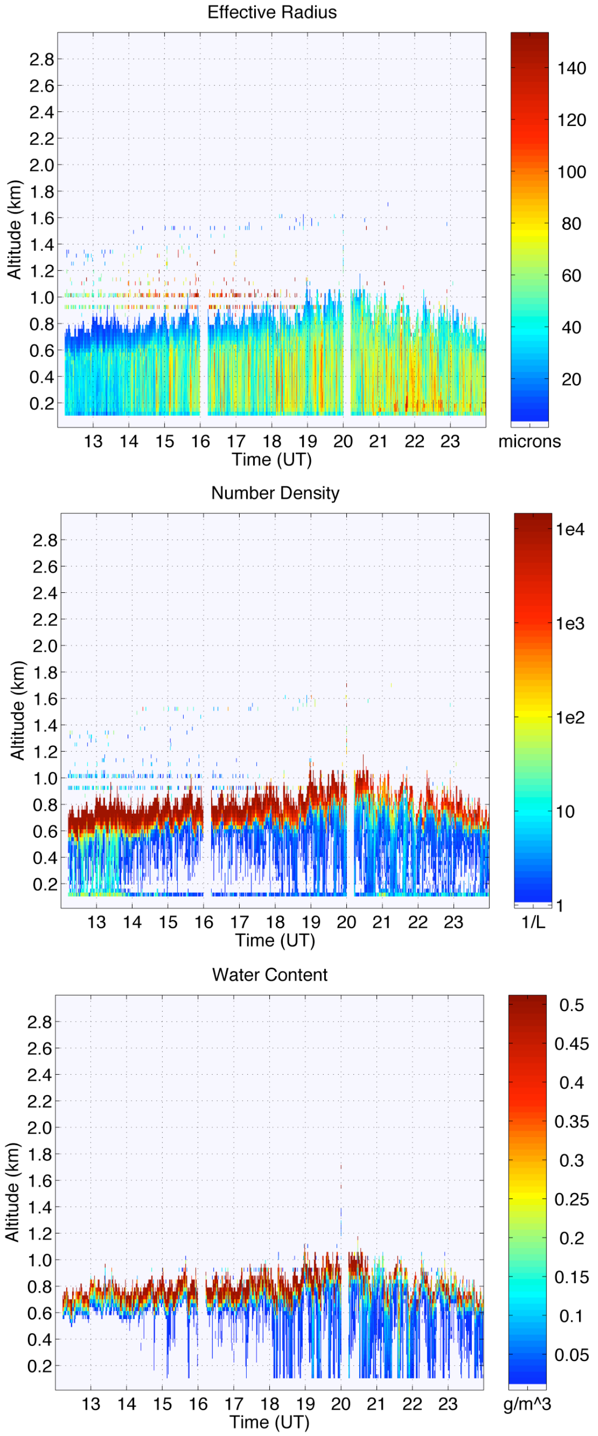


Fig. 2. Effective radius (top), number density (middle) and water content (bottom) retrievals for 9 October 2004.

The center image compares number density values. In addition to the FSSP and 1DC probe, two-dimensional

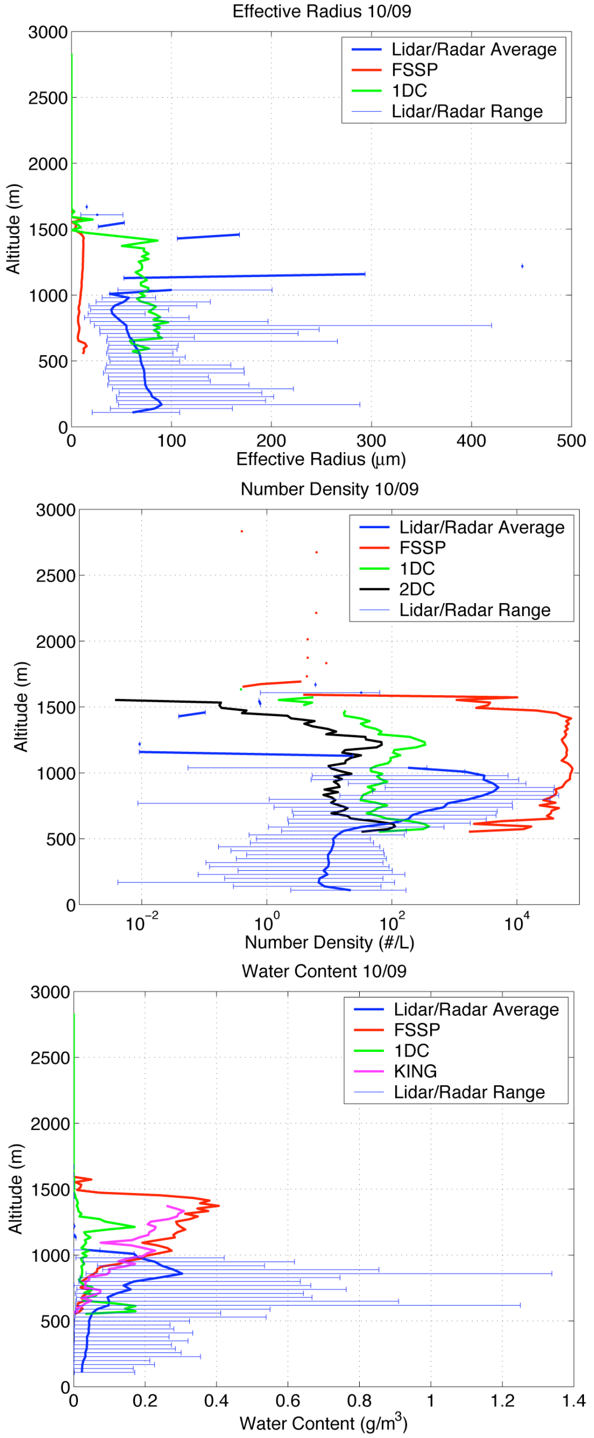


Fig. 3. Vertical profiles of effective radius (top), number density (middle), and water content (bottom) as compared to in-situ measurements taken by the UND Citation.

cloud probe (2DC, nominal diameter range: 125-960 μm) measurements are compared as well. Again, below cloud height, retrieval estimates are comparable to the snow detecting 1DC and 2DC measurements. Once into the cloud, values again fall in between the snow (1DC and 2DC) and liquid (FSSP) measurements. Also important, the slopes and shapes of the retrieval curve are similar to those of the measurement profiles. This indicates that distribution morphology with height is also being detected.

The bottom part of fig. 3 shows profiles for water content. Here, the King Probe (bulk LWC) measurement is also compared. As in the other two comparisons, subcloud retrievals match values of the 1DC probe. Values for water content in the cloud are shown to be too high. This is consistent with the particle sizes being too large. Since water content is dependent upon volume, any error in size will be magnified by a power of three in water content. This is in part compensated for by the low estimate of number density. What is encouraging is the profile shape, and its similarity to that found in in-situ measurements.

It should be noted that these retrievals were all completed without any significant effort put towards optimization of the size distributions for liquid and ice. All assume a modified gamma distribution as discussed in section two. Additional work towards improving distribution estimates is currently underway.

5. SUMMARY

Illustrated here are examples of cloud and precipitation microphysical retrievals derived through advanced ground-based remote sensors. These retrievals are to be used as a source of validation for modeling studies of mixed phase clouds. In addition, the measurements and retrievals themselves provide excellent insight into characteristics of these cloud structures.

6. REFERENCES

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