

A Pathway Toward the Retrievals of the Microphysical Properties of Mixed-Phase Clouds Using Airborne Radar-Lidar Observation

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Abstract: Mixed-phase clouds (MPC) pose significant challenges in climate projections due to the complex physical processes involved and the limited understanding of these processes. A combination of radar and lidar measurements is a plausible pathway for the characterization of MPCs. Recent advances in the light-scattering theory enable us to interpret the backscattering signals measured by lidar instruments into physical parameters on a physics basis. A robust optical property model of mixed-phase cloud hydrometeors is developed and incorporated into a radar-lidar remote sensing algorithm. The sensitivity tests revealed that the present radar-lidar algorithm can characterize the ice/liquid fraction, total water content, and ice crystal effective radius with a reasonable accuracy and liquid droplet effective radius with a fair accuracy.

1. Introduction

Mixed-phase clouds (MPCs) are identified as the leading factors in the high climate sensitivity in both regional and global climate models. MPCs tend to maintain more liquid droplets and be more persistent than those predicted under the assumption of homogeneous mixing of liquid droplets and ice crystals in MPCs where the Wegener–Bergeron–Findeisen process is efficiently activated. Therefore, the spatial phase-heterogeneity of MPCs is considered a potential key to explain the persistency of MPCs [1]. However, the measurement of the spatial heterogeneity of MPCs is extremely challenging. Airborne in-situ cloud probe observations only provide one-dimensional information on the spatial heterogeneity of MPCs. Radar remote sensing is not sufficiently sensitive to liquid droplets in MPCs under the co-existence of liquid droplets and ice crystals. Lidar remote sensing can diagnose a dominant cloud phase in MPCs in an empirical manner and is not suitable for quantitative use in characterizing the microphysical properties of MPCs due to challenges in interpreting the backscattering by atmospheric nonspherical particles.

Recent advances in the light-scattering theory and its computational capabilities will allow us to tackle this long-standing problem in the

characterization of MPCs with radar-lidar remote sensing techniques. The coherent backscattering (CB) mechanism was found to be crucial in the backscattering simulations but was ignored in the light-scattering computational methods based on the geometric optics approximation. This study developed an efficient method to take into account the CB effect for the simulation of the backscattering properties of nonspherical particles in the geometric optics method [2], providing a robust backscattering property simulation in a physically solid manner. The goal of this study is to develop a physics-based radar-lidar remote sensing algorithm and to evaluate the capabilities and limitations of the algorithm for the characterizations of MPCs based on airborne radar-lidar observations.

2. Methods

The backscattering properties of ice crystals and liquid droplets are computed based on the Invariant-Imbedding T-matrix Method (IITM) [3], the Improved Geometric Optics Method (IGOM) with a CB correction [2,4], and Lorenz-Mie code [5]. The shapes of ice crystals are assumed to be those for the Two-Habit Model [6]. The bulk backscattering properties are computed from the scattering properties of liquid droplets and ice crystals by assuming a bi-modal particle size distribution where each mode corresponds to each hydrometeor.

This optical property model is incorporated into a radar-lidar simulator that accounts for the single scattering by particles and the attenuation effects within the target layer and the layers above the target layer [7]. In this study, the lidar wavelength and the radar frequency are assumed to be 355 nm and 95 GHz, respectively. The lidar simulator computes the attenuated backscattering intensity and volume depolarization ratio, whereas the radar simulator computes the attenuated effective radar reflectivity factor.

3. Results and Discussions

The sensitivity tests examine how these radar-lidar signals are sensitive to the MPC microphysical properties. Figure 1 shows the sensitivity of the radar-lidar measurements to the liquid droplet fraction in terms of the extinction coefficient and the effective radius of ice crystals. The total extinction coefficient and liquid droplet effective radius are set to be 0.01 km^{-1} and $10 \text{ }\mu\text{m}$ within the target layer, respectively. It clearly shows that the lidar-derived volume depolarization ratio is useful to quantify the liquid droplet fractions as it is insensitive to the effective radius of ice crystals. The attenuated effective radar reflectivity factor is sensitive to the effective radius of ice crystals and insensitive to the liquid fraction in MPCs. The orthogonality in the sensitivities of the radar-lidar signals implies the high possibility of the robust estimation of these quantities. In addition, the attenuated backscattering intensity can be directly related to the total extinction coefficients.

The only ambiguous parameter for the present radar-lidar remote sensing method is the liquid droplet effective radius. Additional sensitivity tests showed a slight enhancement of the attenuated effective radar reflectivity factor associated with an increase of the effective radius of liquid droplets under the MPC conditions with a relatively small ice crystal effective radius (e.g., $< 50 \text{ }\mu\text{m}$). However, for non-precipitating MPCs, liquid droplet effective radius typically ranges between 5-15 μm , which provides a moderate prior constraint to the retrieval framework.

For the present radar-lidar remote sensing algorithm, an airborne observation is the best preferred observational platform to perform the remote sensing of MPCs because the lidar

signals are attenuated at the point along the beam direction where the optical thickness from the lidar system is about 3-4. Also, the physical scales of the spatial phase-heterogeneity of MPCs can be as low as $< 100 \text{ m}$ according to the airborne in-situ observations [1]. Spaceborne radar-lidar observations may be too coarse to capture the fine-scale structure of MPCs.

In the presentation, if time/space allows, I will show a case study on the MPC characterizations using the airborne radar-lidar observations conducted by the University of Wyoming King Air (UWKA) research aircraft that deploys the Wyoming Cloud Lidar (WCL) and Radar (WCR).

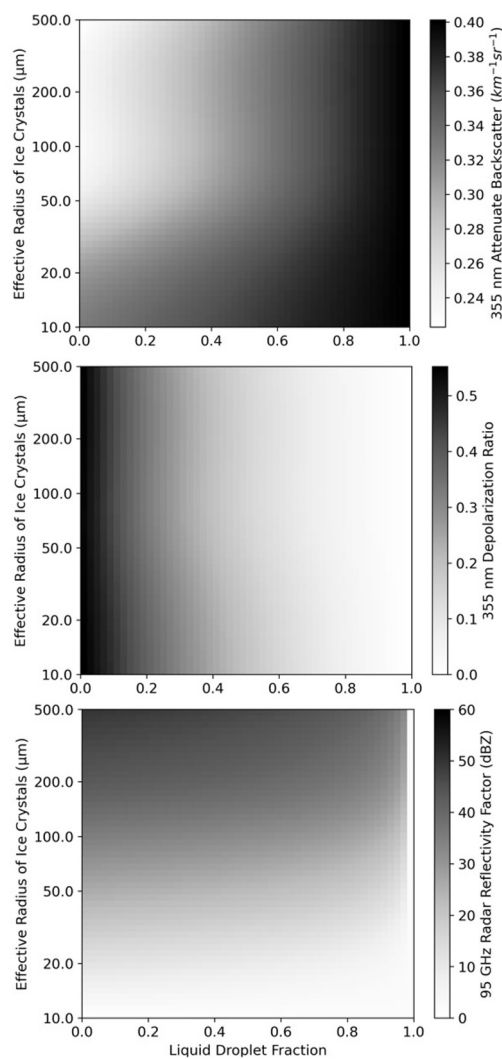


Figure 1. (top) The attenuated backscattering intensity at 355 nm, (middle) the volume depolarization ratio at 355 nm, and (bottom) the attenuated effective radar reflectivity factor at 95 GHz. The horizontal axis is the liquid droplet fraction, and the vertical axis is the effective radius of ice crystals, respectively.

4. Concluding Remarks

This study developed a robust pathway for the characterization of the microphysical properties of MPCs using airborne radar-lidar observations. A robust optical property model enables us to develop a physics-based radar-lidar remote sensing algorithm. The sensitivity tests revealed that the synergistic use of the attenuated backscattering coefficients and volume depolarization ratios at 355 nm from lidar measurements and effective radar reflectivity factors at 95 GHz from radar measurements significantly enhances the information content of MPCs, demonstrating the potential of radar-lidar remote sensing approach based on a physics-based algorithm for characterizing MPC properties.

5. References

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