US CLIVAR Micro2Macro: Origins of Climate Change Uncertainty Workshop

University of Wyoming

Airborne Radar-Lidar Remote Sensing for Characterizing The Microphysical Properties of Mixed-Phase Clouds

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Background and Objective

Mixed-phase clouds (MPCs) can occur anywhere across the globe, influencing the global radiation budget and hydrological cycle. **The macroscopic characteristics of MPCs (e.g., radiative properties and lifetime) are partly governed by cloud glaciation processes**, which transform MPCs into ice clouds. In these processes, the Wegener-Bergeron-Findeisen (WBF) process plays a pivotal role by growing ice crystals at the expense of supercooled liquid water through vapor exchanges. Numerical models have long struggled with accurate MPC simulations, partly due to a poor representation of cloud glaciation in MPCs, as the models assume a spatially homogeneous MPC at a model grid scale (~10^2–10^4 m). **Due to persistent challenges in measurement techniques for quantitatively characterizing fine-scale structures (<10^2 m) of MPC microphysical properties, the impact of spatial heterogeneity on cloud glaciation processes has been poorly understood** (Figs. 1-2).

Motivated by the community's need for such measurements in MPCs, **this study explores the capabilities of the NSF University of Wyoming King Air (NSF/UWKA) remote sensing measurements for characterizing the fine-scale structures of microphysical properties in MPCs.**

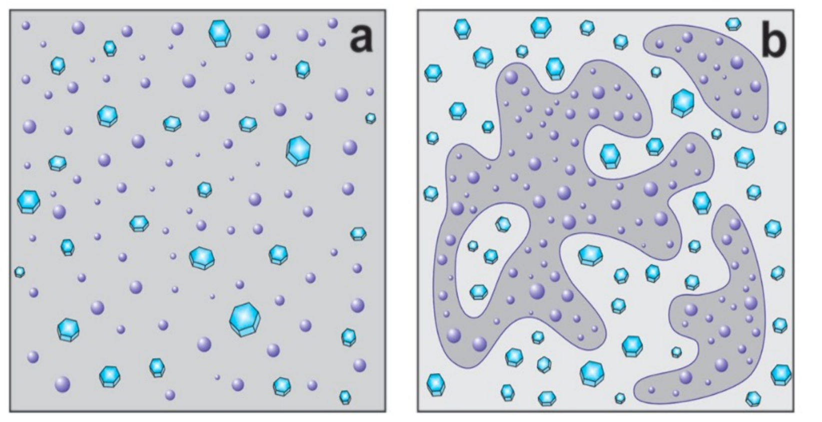

Fig.1. Conceptual diagrams of (a) the genuine mixed-phase clouds and (b) conditional mixed-phase clouds. Adapted from Korolev and Milbrandt (2022).

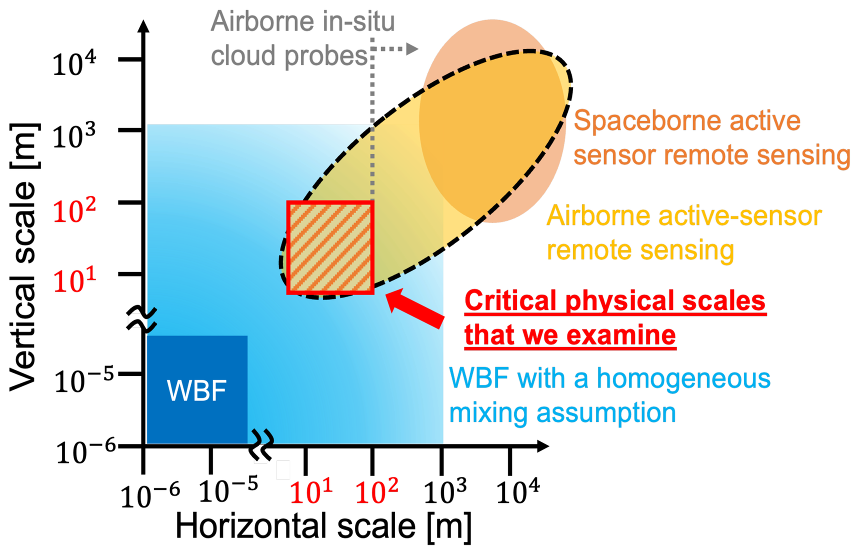

Fig.2. The physical scales of the WBF process and those of the microphysical properties that can be described with individual measurement methods.

Forward Modeling and Sensitivity Tests

The sensitivity test shows that WCR-WCL measurements are sensitive to the profiles of extinction coefficients, liquid droplet fractions, and the effective radius of ice crystals (Fig. 6). The inclusion of KPR enhances sensitivity to larger ice crystals. Notably, **the depolarization ratio is crucial for retrieving the liquid/ice fractions in MPCs.**

Table 3 Retrieval algorithm setup. †Note that retrieval of the liquid droplet effective radius is challenging under the co-existence of liquid and ice in clouds.

Items	Variables
Measurement vector	▪ WCL attenuated backscatter ▪ WCL volume depolarization ratio ▪ WCR radar reflectivity factor ▪ KPR radar reflectivity factor
State vector	▪ Total extinction coefficient ▪ Liquid droplet fraction ▪ Liquid droplet effective radius† ▪ Ice crystal effective radius

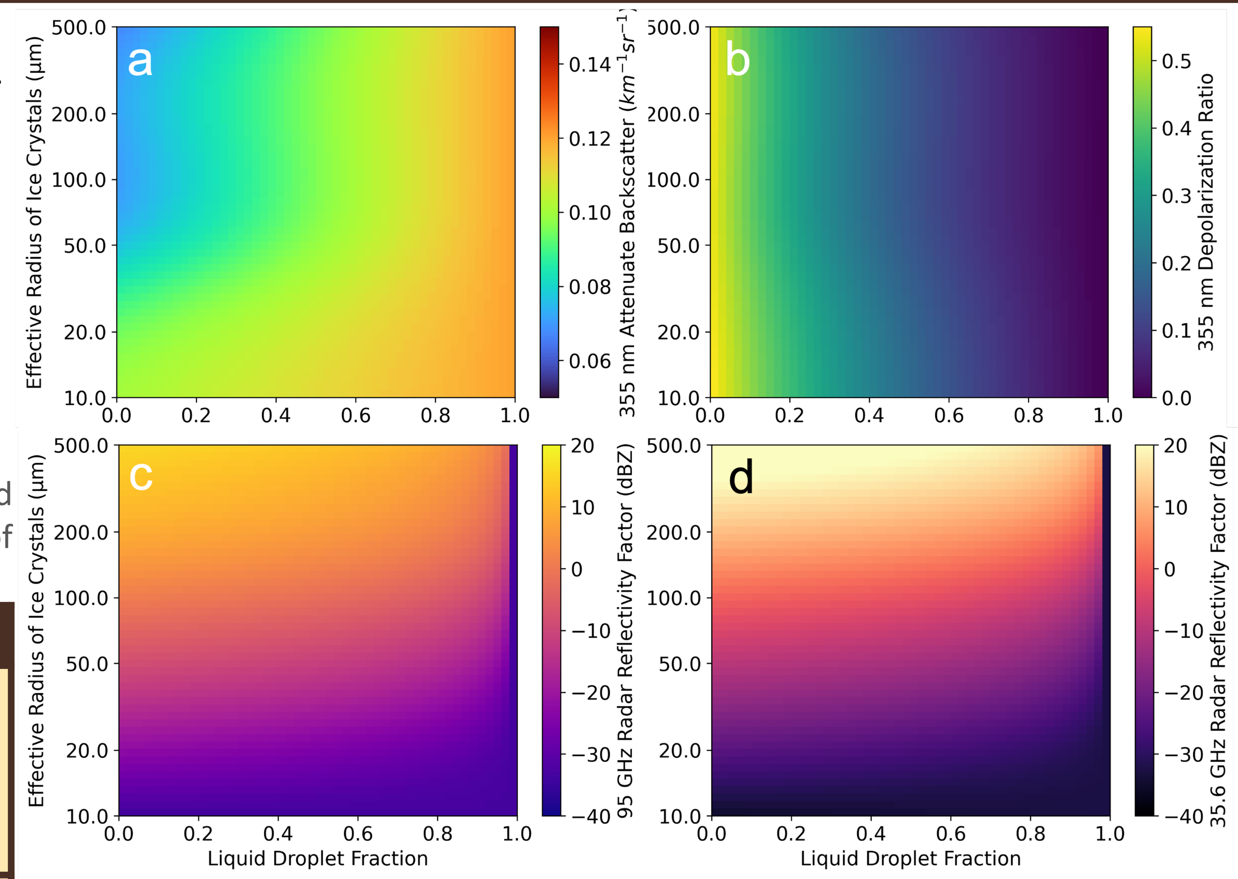

Fig.6 The sensitivities of the radar-lidar measurements to the ice crystal effective radius and liquid droplet fractions, including (a) the attenuated backscattering coefficient at 355 nm, (b) the volume depolarization ratio at 355 nm, (c) the attenuated effective radar reflectivity factor in W-band (94.9 GHz), and (d) that in Ka-band (35.6 GHz). The liquid droplet effective radius is 10 μm in this case.

A Fully Physics-based Remote Sensing Method

A fully physics-based remote sensing algorithm does not rely on empirical parameters crucial to retrievals (e.g., the lidar ratio). Table 1 shows the current setup of the retrieval framework for numerical experiments. The striking feature of this method is the use of a physics-based MPC optical property model. Saito and Yang (2023) derived a formula to incorporate coherent backscattering (CB) into scattering simulations in geometric optics, enabling robust calculation of the backscattering properties of large ice crystals. **This allows us to incorporate all lidar signals such as attenuated backscattering and depolarization ratios into the retrieval framework.** Fig. 3 shows simulations of the backscattering properties of ice crystals.

Table 1 The list of the setups for the full physics-based method.

Items	Assumptions and approximations
Radar-Lidar Simulator	▪ Single-scattering approximation ▪ Attenuation above and within the layer
MPC Optics	▪ Mie scattering for liquid droplets ▪ IITM + IGOM with CB correction for ice crystals (Saito and Yang, 2023)
Inverse Solver	▪ Optimal Estimation (Rodgers, 2000) ▪ Levenberg-Marquardt Method

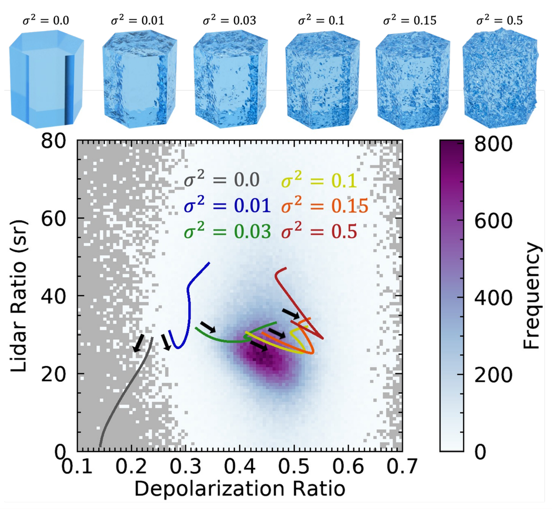

Fig.3 Two-dimensional histogram of the lidar and depolarization ratios of cold ice clouds from spaceborne lidar observations and simulations. Color lines are for various ice crystal models illustrated on the top. (Saito and Yang, 2023)

Retrieval Performance Evaluation

The retrieval performance evaluation based on synthetic airborne measurement experiments is shown in Fig. 7. Random noise at 30% relative to the measurement signals is added to the simulated measurements. A combination of radar and lidar measurements deployed on the NSF/UWKA can estimate the microphysical properties listed in Table 3†. The present remote sensing algorithm, when combined with airborne radar-lidar measurements, shows promise in characterizing the fine-scale structure of MPC microphysical properties. Given the advanced remote sensing capabilities, **it is time to revisit the outstanding challenges in understanding the role of the spatial heterogeneity of MPC microphysical properties at scales down to ~10 m** (Fig. 1).

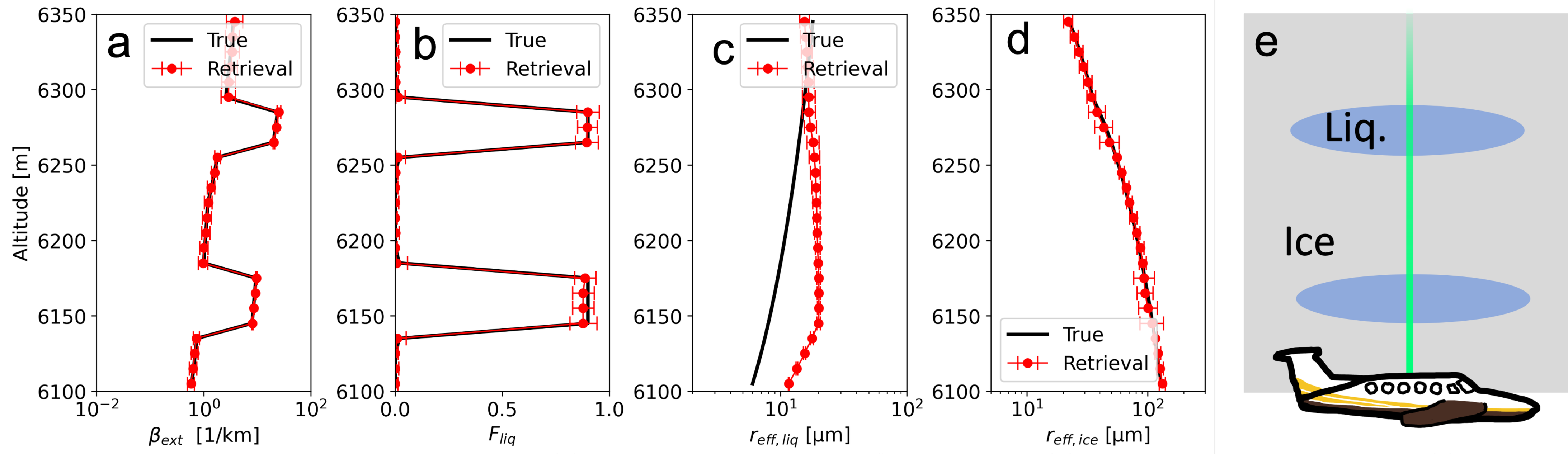

Fig.7 The retrieval tests, including the profiles of (a) the extinction coefficients β_{ext} at 355 nm, (b) the liquid droplet fractions F_{liq}, (c) the liquid droplet effective radii $R_{eff,liq}$, and (d) the ice crystal effective radii $R_{eff,ice}$, and (e) an illustration of MPC in the retrieval performance experiments.

NSF/UWKA Remote Sensing Instruments

The key NSF/UWKA remote sensing instruments include WCR, WCL, and KPR (Table 2). These instruments provide cross-sectional radar-lidar signals of MPCs with fine spatial scales (Fig. 4).

Table 2 The list of NSF/WUKA remote sensing instruments.

Instruments	Note
Wyoming Cloud Radar (WCR)	▪ Frequency at 94.94 GHz ▪ Along-beam resolution: **≥7.5–37.5 m** ▪ Along-track resolution: **≥4–5 m**
Wyoming Cloud Lidar (WCL)	▪ Wavelength at 355/351 nm ▪ Along-range resolution: **≥1.5–3.75 m** ▪ Along-track resolution: **≥4.5 m**
Ka-band Precip. Radar (KPR)	▪ Frequency at 35.6 GHz ▪ Along-beam resolution: **≥30.0 m** ▪ Along-track resolution: **≥20 m**

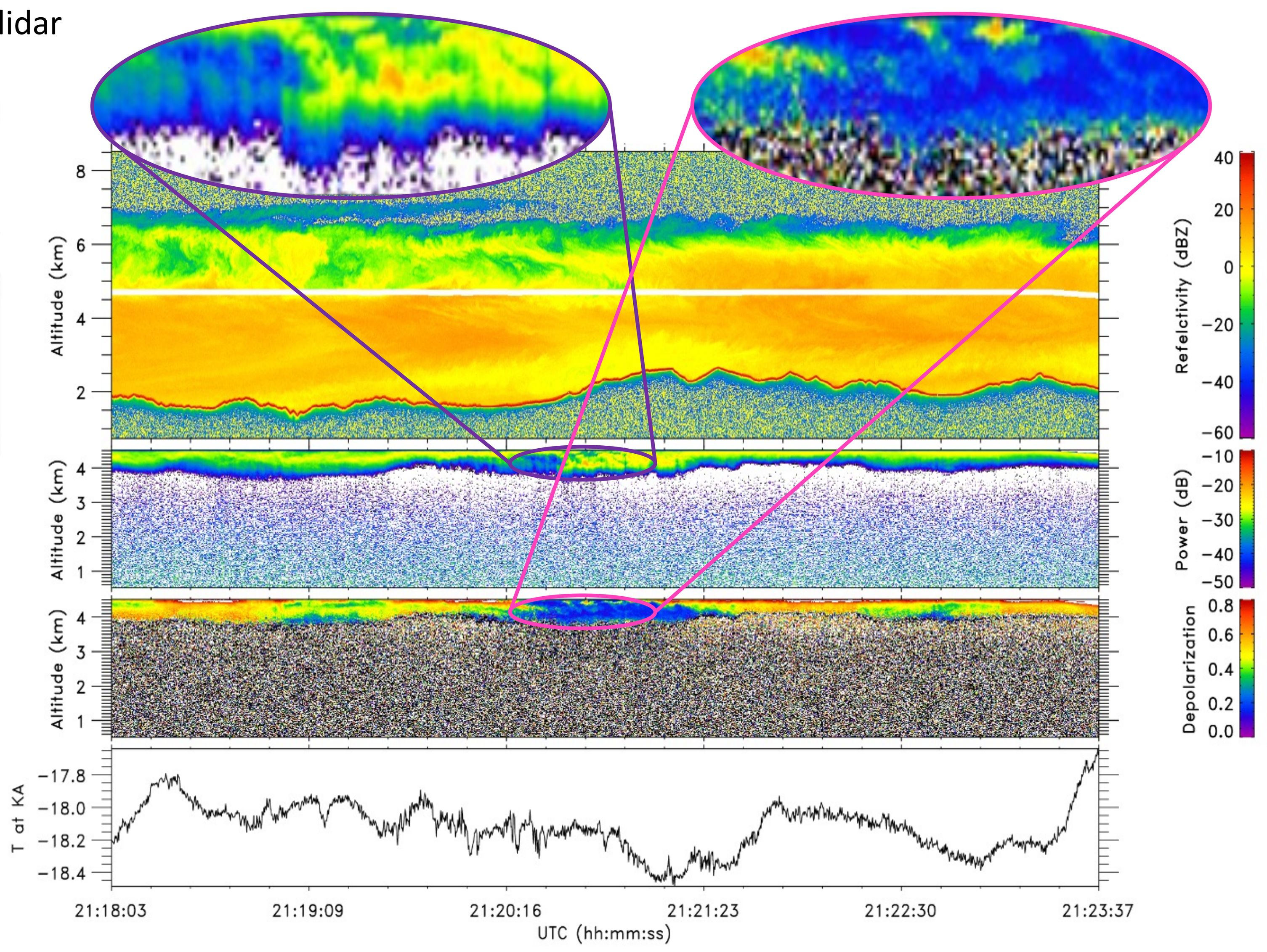

Fig.4 The examples of the UWKA-deployed instrument measurements during the SNOWIE field campaign.

Summary and Outlook

1. **A fully physics-based radar-lidar remote sensing algorithm was developed for use with NSF/UWKA remote sensing measurements.** The key effort was the development of a robust MPC optical property model.
2. **The sensitivity tests and retrieval performance evaluation demonstrated a pathway for characterizing the microphysical properties of MPCs.** MPC microphysical properties *could* be available at such fine spatial resolutions.
3. **A more precise estimation of measurement–model errors is necessary to analyze NSF/UWKA remote sensing datasets using this algorithm.** Estimating the uncertainty of the retrievals is the next key focus of this work.

Acknowledgments and References

This work is supported by the Faculty Startup offered by the Department of Atmospheric Science at the University of Wyoming. The numerical computations were performed with NCAR Derecho Supercomputer.

1. Saito and Yang (2023), *Geophys. Res. Lett.*, **50, e2023GL10475**.
2. Korolev and Milbrandt (2022), *Geophys. Res. Lett.*, **49,** e2022GL099578.
3. Rodgers (2000), *World Scientific Publishing Co.*, https://doi.org/10.1142/3171