We developed a forward model to calculate the radar signals of ice crystals given limited information from ice growth models. By generating a variety of ice crystals, we simulated radar signals for a range of particle shapes. Using these results, the probabilistic forward model accurately calculates radar signals from limited model information and provides an estimate of the uncertainty.
References:

Data Sources: Atmospheric Radiation Measurement (ARM) X-band Scanning ARM Precipitation Radar (XSAPR) radar data from Utqiagvik, AK, computational resources from The Department of Atmospheric Science and Meteorology at the Pennsylvania State University.

Technical Description of Figures:
**Graphic 1 (left):** Comparison between the polarimetric radar variable differential reflectivity (ZDR) for detailed scattering calculations for each generated ice crystal shape (x axis) and the corresponding ZDR simulated using the forward model with the physical properties (mass, size, and aspect ratio) of the detailed shape (y-axis). The colors represent the counts of calculation pairs within each bin of true ZDR and forward-simulated ZDR. The majority of the comparisons are close to the one-to-one line (dashed black) indicating that the forward model can accurately simulate the variability in the ZDR of the detailed shapes.

**Graphic 1 (right):** A sample of the first 96 (of 500) generated ice crystal shapes used to determine the radar forward model. These shapes represent the top view of crystals with a prescribed depth. The ratio of this depth to the horizontal crystal length determines the particle aspect ratio which is varied in the calculations used to develop the forward model.

Scientific significance, societal relevance, and relationships to future missions: This work allows for the more rigorous evaluation of ice microphysical modeling. Our understanding of these processes is limited, given the complexity of natural ice particles in the atmosphere and the fact that their growth depends on interactions between ice particles, as well as the temperature, humidity, and liquid water content of the atmosphere. The ability to take simulated ice particle properties (e.g., mass, size, shape) and accurately calculate their radar signatures allows for radar observations to help constrain the uncertainties found in microphysical models. Because microphysical models by necessity use simplified representations of ice particles to simulate their growth, there is ambiguity in the detailed shapes that these simplified particles represent. Therefore, there is also uncertainty in the radar signatures of these simplified representations of ice particles. The forward model developed herein uses the variability of radar signatures for a set of model-simulated ice particle properties to determine the corresponding uncertainty in the radar signatures associated with the simplified model representations. Thus, the relatively simple particles simulated by the ice growth model can be appropriately compared to radar observations of natural ice particles. This forward model also allows for a way to evaluate retrievals of ice particle properties from spaceborne radar systems such as those found on the GPM core observatory. For example, ice particle properties retrieved using only the dual-frequency radar measurements from GPM can be independently evaluated using the forward model for coincident ground-based polarimetric radar data. The degree of correspondence between the simulated ground radar signatures using particle properties retrieved from spaceborne radar and the actual ground radar measurements determines the validity and limitations of the spaceborne retrievals. These results can then motivate specific areas of improvement needed in future spaceborne remote sensing missions that aim to retrieve ice particle physical properties globally. Advances in retrieving these properties will improve global estimates of falling precipitation and improve the representations of ice growth processes in global weather and climate models. These improvements will have a substantial impact for the Aerosol, Cloud, Convection, and Precipitation (ACCP) concept currently being studied, as the objectives of this Decadal Survey Designated Observable include understanding the underlying processes behind clouds and precipitation.

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By approximating the shortwave spectra in the cloud-clear transition zone as a linear combination of purely clear and purely cloudy spectra, we can characterize cloud optical thickness and cloud droplet effective radius in the transition zone. When applying this method to the measurements of a ground-based shortwave spectroradiometer in continental and maritime conditions, we found that cloud optical depth consistently decreases in both cases, but droplet size decreases much more substantially for the continental regime, suggesting different mixing processes for the two types of clouds.
References:

Data Sources: Atmospheric Radiation Measurement (ARM) data set available at https://www.arm.gov/data.

Technical Description of Figures:
*Graphic 1:* Schematic illustration of two limiting scenarios of the air entrainment and mixing processes: (a) the homogeneous mixing reduces the size of all cloud droplets but does not substantially change the number of droplets due to quick mixing of clouds and drier air; (b) the inhomogeneous mixing reduces the droplet number concentration for droplets of all sizes but does not change the droplet size spectrum because cloud droplet evaporation occurs before dry air penetrates the entirety of the cloud.

*Graphic 2:* (Top) Schematic illustrations of cloud edge properties from Pinsky and Khain (2018). Here LWC is liquid water content and RH is relative humidity. (Bottom) the shortwave array spectroradiometer-zenith (SASZe) instrument capable of resolving the fine structure in cloud edges.

Scientific significance, societal relevance, and relationships to future missions: Entrainment of dry air into clouds and mixing of dry air with cloudy air affects cloud amount and cloud microphysics. However, it is unclear whether the mixing process is predominantly homogeneous, inhomogeneous, or a combination of the two. The cloud edge area is an important region for understanding the mechanisms of the cloud mixing process. Yang et al. (2019) study demonstrated that the variation of cloud droplet size in cloud edges of continental clouds (more homogeneous mixing) is characteristically different from that for maritime clouds (more inhomogeneous mixing), suggesting different mixing mechanisms. Our results can be used to test mixing schemes in cloud models. Moreover, our findings on the transition zone between clear and cloudy air can potentially lead to improvements in space-based estimates of aerosol radiative forcing and aerosol indirect effects as a function of cloud and aerosol microphysical properties and to a better understanding of the spatial structure of cloud boundaries and their droplet size distributions.

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