Science Report on the DOE funded research (9/2017 to 9/2021)

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Ice processes in Antarctica: identification via multi-wavelength active and passive measurements and model Evaluation

Federal Award Identification Number: **DE-SC0017967**

Organization: Office of Biological & Environmental

Project Period: 09/15/2017-09/14/2020 (a no-cost extension was granted until 9/14/2021).

OBJECTIVES:

The project had three main scientific goals.

1) Development of cloud microphysics retrievals from multi-wavelength radar observations and ancillary observations, generally applicable at ARM sites;
2) Characterization of ice microphysical properties and ice processes during AWARE by exploitation of 1);
3) Evaluation and improvement of the NASA GISS ModelE3 climate model, including selection of case studies for combined goals of (i) running side-by-side using large-eddy simulation (LES) and ModelE3 in single-column model (SCM) mode and (ii) fingerprinting cloud processes in multi-wavelength radar observations.

ACCOMPLISHMENTS

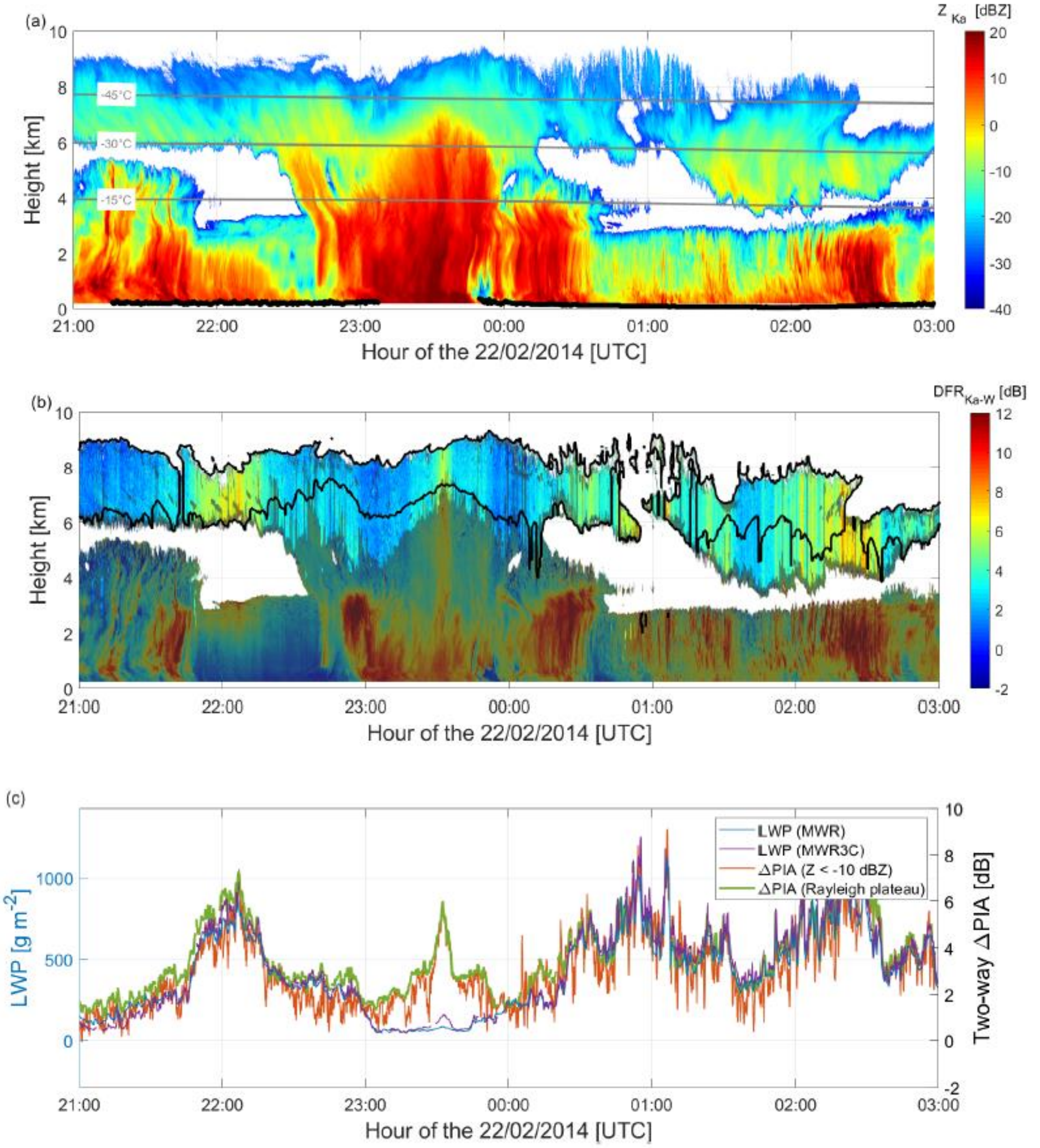
During the AWARE field campaign, a unique remote sensing dataset has been collected with radar, radiometer and lidar observations. This, first, has fostered the development of techniques suited to properly quality controlling and cross calibrating the different radars (A), and, second, to retrieve ice microphysics (B).

A) <u>Development of cross-calibration and attenuation correction procedures for millimeter cloud radars</u>

Before using multi-frequency radar data in quantitative retrieval, a procedure to properly cross-calibrate the radars and produce sensible dual wavelength ratios is needed. In addition, a robust attenuation correction algorithm is desirable in order to pass from measured dual wavelength ratios to effective dual wavelength ratios (which are directly related to the size of the scattererer within the backscattering volume).

We have developed a procedure based on Rayleigh segments of the clouds, i.e. regions containing scatterers that can be considered small compared to all radar wavelengths. Our novel approach as described in Tridon et al., 2020 (see also example of the method in Fig. 1) goes far beyond commonly used Ze-threshold approach. Instead we investigate vertical gradients of DWRs to determine regions being dominated by Rayleigh targets. In this way we are able to estimate PIA where the standard Ze-threshold method would not be applicable. When the PIA is predominantly produced by cloud liquid droplets, this technique alone can provide accurate estimates of the liquid water path. When combined with microwave radiometer (MWR) observations, this methodology paves the way towards profiling the cloud liquid water and/or quality flagging the MWR retrieval for rain/drizzle contamination and/or estimating the snow differential attenuation. In a recent study (Kalogeras and Battaglia, 2021) we have also developed an attenuation correction methodology for polar cloud conditions based on a multi-instrument suite of sensors like available at ARM sites (see example in Figure 2). Finally, we have developed (Kalogeras et al., 2021) an ice/liquid phase partition which is based on a per-pixel, neighborhood-dependent algorithm. The idea is to examine the mean values of locally sampled probability distributions of radar-based observables (like spectral width and vertical gradients of reflectivity factors and radial velocities) and then to compare those against the means of climatologically derived, per-phase probability distributions.

Figure 1. Case study observed at the ARM facility in the Hyytiälä Forestry Field site on 21 February 2014. Time-height [UTC-km] plots of the (a) Ka reflectivity with liquid cloud base detected by the co-located lidar as magenta points and (b) Ka-W DFR filtered for non-Rayleigh targets (gray shading). (c) Time series of the Ka-W DFR at cloud top, i.e. the two-way PIA derived with the Ze-threshold approach and with the Rayleigh plateau method (scale on the right y-axis) overlaid by the LWP measured by the MWRs (scale on the left y-axis). The black lines show the -45, -30 and -15°C isotherms in (a) and the uppermost ZKa = -10 dBZ contour in (b). Extracted from Tridon et al, 2020.



Results highlight that the optimal supercooled liquid water detection skill levels are realized for the radar variable combination of spectral width and reflectivity vertical gradient, suggesting that radar-based polarimetry, in the absence of full LDR spectra, is not as critical as Doppler capabilities.

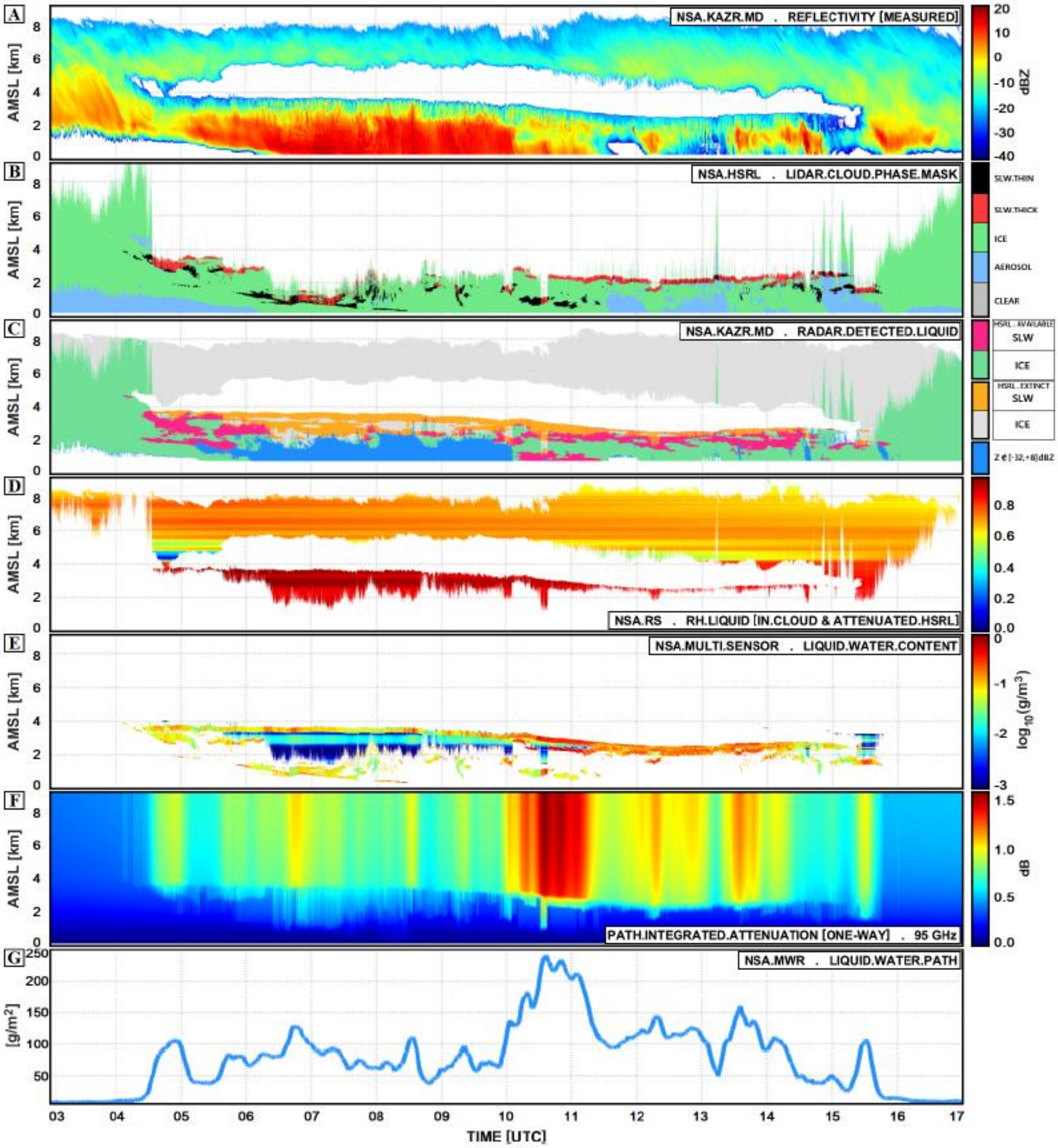


Figure 2. Example of W-band radar attenuation correction methodology based on Ka-band radar, lidar, MWR observations (plus radio-soundings).

B) **Development of a triple frequency ice microphysics retrieval (including a consistent single scattering database for ice crystals)**

When retrieving ice properties with multi-wavelengths system it is important to use scattering database which are consistent across the frequency spectrum. We have built scattering properties for different ice crystals based on the Self-Similar Rayleigh Gans Approximation (Kneifel et al., 2020, Ori et al, 2021). We have then developed two ice microphysical

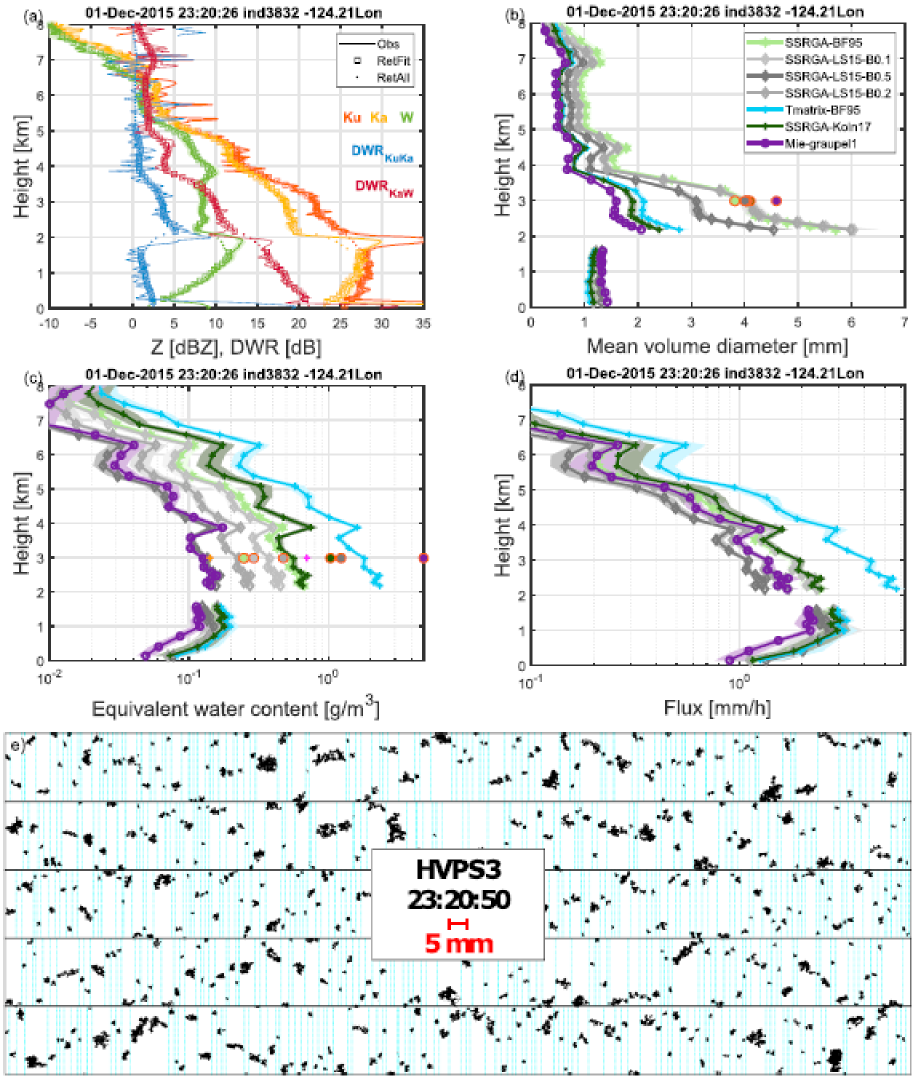


Figure 3. Profiles of observed Ku, Ka, W reflectivity, and corresponding Ku-Ka and Ka-W dual wavelength ratios (DWRs) in dark orange, orange, green, blue, and magenta, respectively (a), retrieved Dm (b), WC (c), and corresponding flux (d) at −124.21◦E during the more effective aggregation period. Shadings show the retrieval error. The collocated in situ Dm and WC are indicated by colored disks and the corresponding images of the ice crystals are shown in panel (e). WC = water content; SSRGA = Self-Similar Rayleigh-Gans Approximation. Extracted from Tridon et al., 2019.

retrievals: the first is based on an optimal estimation (Battaglia et al., 2020; Tridon et al., 2019), the second on a statistical approach trained with in-situ air-borne observations (Mroz et al., 2021). Since there were no validation data during the AWARE campaign we have validated the algorithms with independent datasets. The Tridon et al., 2019 retrieval uses an ensemble approach where different scattering models are tested and an ensemble average is performed for the ones that achieve convergence. An example of the retrieval for a full profile is shown in Figure 3. The retrieval is validated with quasi-coincident aircraft observations. Even with the constraint of three frequencies, the uncertain degree of riming for the ice crystals (and its correspondent scattering model) remains the key factor affecting the retrieval uncertainties. Note that the retrieval has been generalized to rain as well with some applications demonstrated with data collected at the ARM site in Oklahoma (Tridon et al., 2019). The statistical retrieval of Mroz et al. 2021, based on Bayes' rule with riming parameterised by the "fill-in" model, is tested on multi-frequency radar data collected during the ESA-funded Radar Snow Experiment For Future Precipitation Mission. During this campaign, in situ microphysical probes were mounted on the same airplane as the radars. This nearly perfectly co-located dataset of the remote and in situ measurements gives an opportunity to derive a combined multi-instrument estimate of snow microphysical properties that is used for a rigorous validation of the radar retrieval. Results suggest that the triple-frequency retrieval performs well in estimating ice water content (IWC) and mean mass-weighted diameters obtaining root-mean square errors of 0.13 and 0.15, respectively, for log10IWC and log10Dm. The retrieval of the degree of riming is more challenging, and only the algorithm that uses Doppler information obtains results that are highly correlated with the in-situ data. The information of Doppler measurements for retrieving degree of riming has been confirmed by the work of Oue et al, 2021, Kneifel and Moisseev, 2020, and Mason et al., 2018.

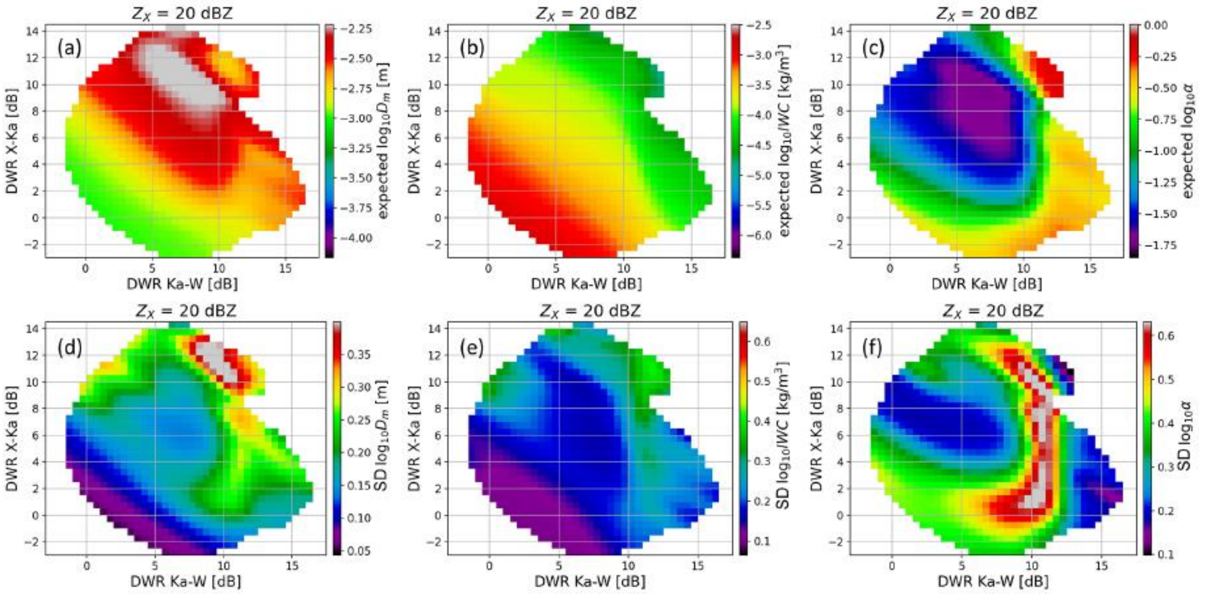


Figure 4. Example of the statistical retrieval for a fixed 20 dBZ reflectivity at X-band: the expected values of log10Dm, log10IWC and log10_rm in the $DWR_{X\text{-}Ka}$–$DWR_{Ka\text{-}W}$ space for ZX D20 dBZ. (d–f) Uncertainties in the quantities presented in the top row (see the colour bar captions). The inverse model is derived from the in situ airborne PSD measurements during the MC3E, IPHEx, OLYMPEX and HAIC/HIWC campaigns.

The tools developed in A) and B) have been exploited to characterize ice microphysics and microphysical processes (C).

C) <u>Identification of microphysical processes</u>

Unfortunately, the W-band radar during AWARES has stopped working at the beginning of February 2016, which has not enabled a year-long characterization of ice microphysics at McMurdo. Therefore, the analysis had to focus on a few case studies. Figure 5 extracted from Lubin et al., 2020 shows a two-dimensional histogram of the data collected at McMurdo during 10 January 2016 from the X–Ka- and W-band ARM radars. While most of the data are concentrated around the origin (0 dB, 0 dB), thereby corresponding to small ice crystals that produce the same reflectivities at all frequencies, histogram bins with large DWRs signal the presence of larger ice crystals. Following the rationale proposed by Kneifel et al. (2015) the three different branches indicated by the continuous, dotted and dashed lines correspond to different growth mechanisms. For example, the typical hook signature (continuous line) is likely associated with low-density aggregates, while the points with large Ka–W and small X–Ka DWR (dashed line) are linked to denser and more spherical particles. Surprisingly, the strength of the observed multifrequency radar signatures are overall in a similar range (both DWRs exceeding 10 dB) as observed during the deployment of the AMF2 at the Biogenic Aerosols–Effects on Clouds and Climate (BAECC; Petäjä et al. 2016) campaign in Finland (Kneifel et al. 2015). The unexpected strong multifrequency radar signatures revealed during AWARE indicate that growth processes such as aggregation and riming play an important role in the processes related to snowfall production in Antarctica—at least in areas with sufficient supply of moisture such as close to the coast. These findings have been confirmed by Tridon et al., 2021, who analyze the full AWARE dataset available and identify a unique mode in the McMurdo dataset appearing at quite cold temperature when considering triple frequency signatures (Figure 6). Such a comparison of growth signatures as function of temperature comparing mid-latitutdes and Antarctica has never been done before. These statistics are quite valuable for evaluating models as done for example in Ori et al., 2020. The case study of the 4th January 2016 featured a persistent layer of unexpectedly pronounced triple-frequency radar signatures but only a relatively modest amount of supercooled liquid water. In-depth analysis of the radar observations suggests that such signatures can only be explained by the combined effects of moderately rimed aggregates or similarly shaped florid polycrystals and a narrow particle size distribution (PSD).

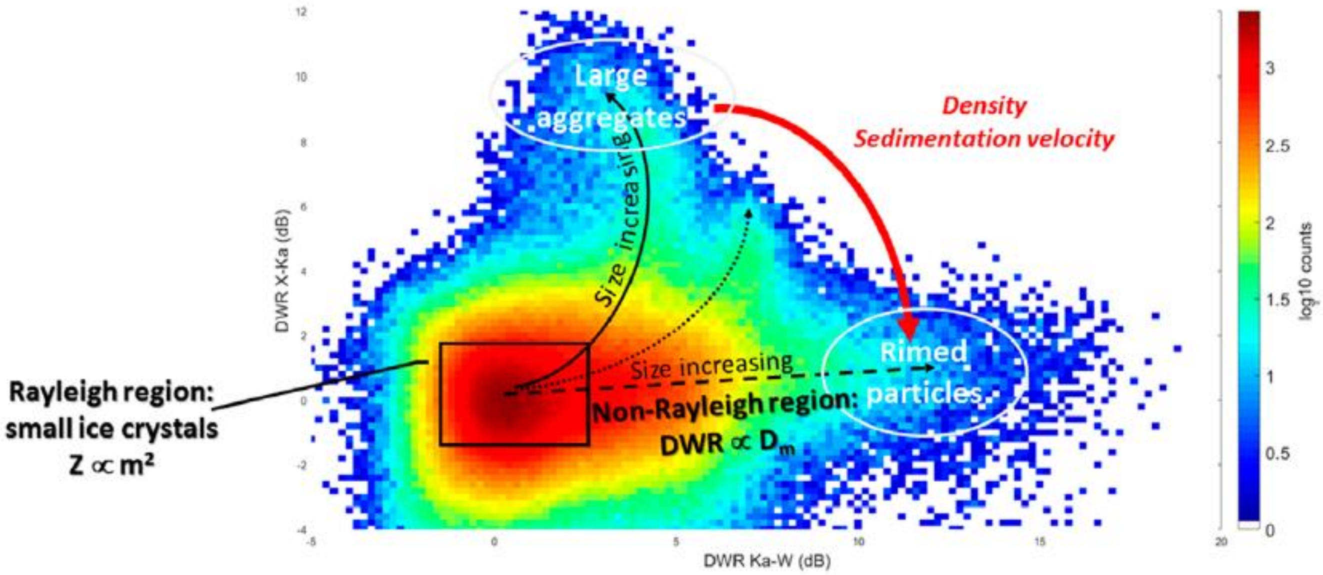
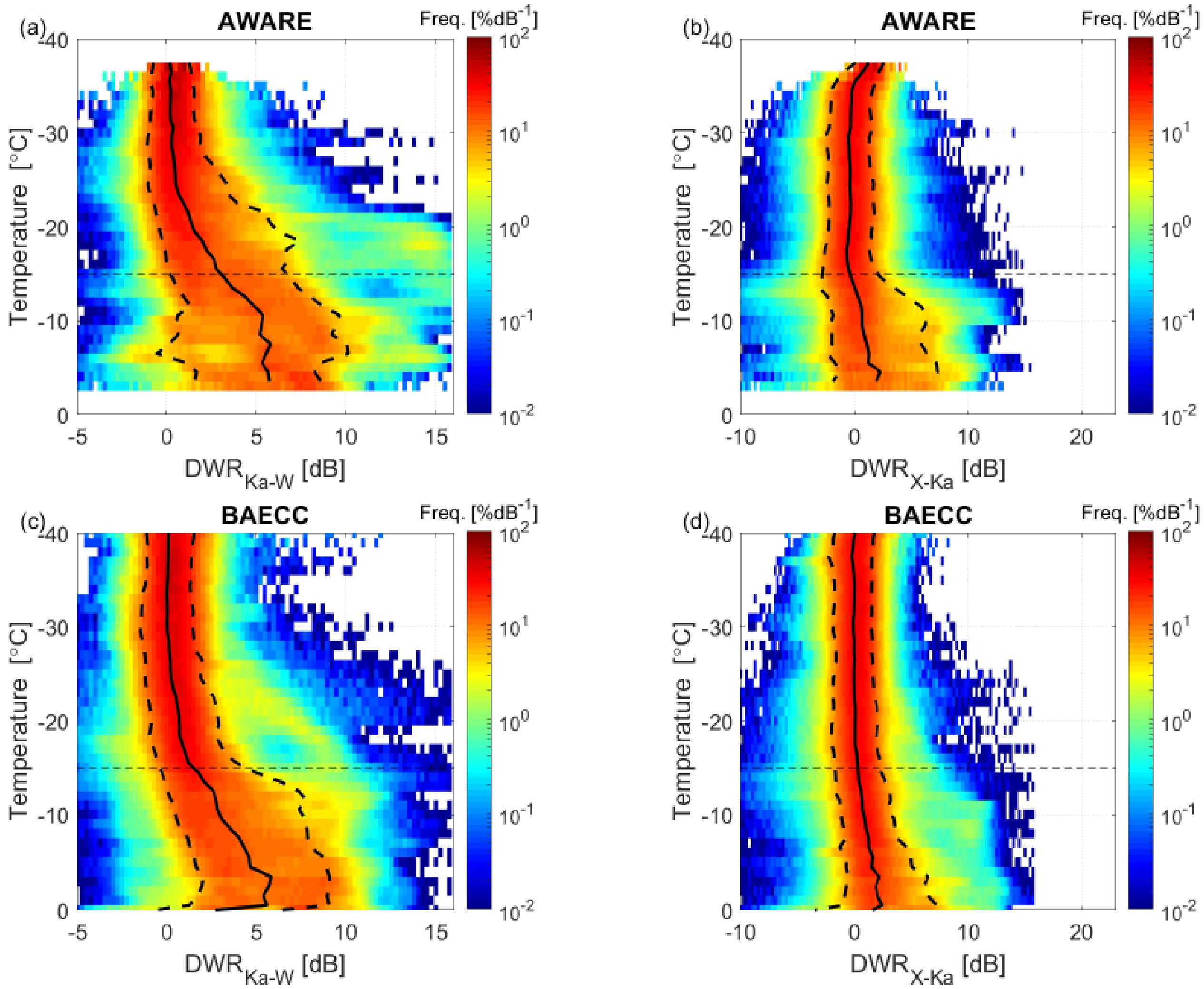


Figure 5. Two-dimensional histogram of DWR Ka–W vs DWR X–Ka measurements collected by the X–Ka and W-band ARM radars during 10 Jan 2016 at McMurdo Station. Negative DWRs are unexpected and might be caused by imperfect radar volume matching and measurement noise. Away from the Rayleigh region (black square) different growth regimes can be identified (continuous, dotted, and dashed lines). The red arrow points toward ice particles characterized by higher densities and larger sedimentation velocities.

D) Modeling with LES, SCM, GCM, and bin microphysics in 1D

As analysis of the triple-frequency radar observations proceeded, the modeling group began with a study of persistent highly supercooled drizzle identified later in the campaign. Modeling aimed to answer the question: what dynamic and aerosol conditions could support the observed persistence of such highly supercooled drizzle? Because precipitation processes feed-back on aerosol properties, we took a Lagrangian simulation approach, following the mean in-cloud horizontal winds with the model domain. To obtain a plausible initial profile for simulations, we first extracted large-scale vertical motion from a back-trajectory at all heights within cloud from ERA5 reanalysis fields and then applied those in reverse time to the observed profile. We then smoothed the initial profile to remove features that the observed highly supercooled cloud itself introduced, obtaining a plausible initial condition. We then ran the DHARMA LES forward from that initial profile, confirming that large-scale ascent led to cloud formation, and that the cloud processes introduced a sharp inversion and decoupled turbulent layer similar to that observed. Finally, we confirmed that relatively low droplet number concentrations (20 cm^{-3}) and ice crystal concentrations (0.1 L^{-1}) were consistent with sustained drizzle occurrence. The simulated cloud, with sustained drizzle and snow from cloud base as observed, also reproduced a unique two-layer structure below cloud base, apparently associated with drizzle evaporation. Results of these initial LES simulations were reported in JGR (Silber et al. 2019a). In the course of this work,

Figure 6 Density plots of $DWR_{Ka\text{-}W}$ (a,c) and $DWR_{X\text{-}Ka}$ (b,d) as function of temperature for AWARE (a,b) and BAECC (c,d) datasets.The dashed lines indicate the 10th and 90th percentiles.



Fridlind contributed to completion of earlier work evaluating ERA5 and AMPS model results (Silber et al. 2019b).

A leading goal of this project was to prepare an SCM case study for evaluating the ability of ModelE3 to simulate unique Antarctic cloud conditions. This LES case study of sustained highly supercooled drizzle and snow was subsequently prepared for ModelE3 by adding a plausible aerosol specification derived more robustly from observations. Contributions from Dr. Lynn Russell led to derivation of aerosol lognormal modes from the AWARE observations. Although these were observed at the surface, they were deemed nonetheless more representative of conditions aloft than other data sources. However, when they were implemented in LES, it came as a surprise that turbulence no longer developed in the 8-hour cloud formation period prior to advection over McMurdo, thus leading to an inconsistency with observations. After head scratching, we realized that gravity waves that are common in stable atmospheres similar to that associated with the cloud formation period, could lead to irreversible droplet activation. This idea had been considered during initial case study development, but the typical (lower latitude) maritime aerosol used in the first simulations required much weaker supersaturations to activate owing to a larger modal diameter than typically observed over McMurdo. Once the specified aerosol were smaller, gravity waves became important to both droplet activation and, by extension, turbulence formation. These findings were reported in GRL (Silber et al., 2020), along with an analysis of cloud layer stability over both McMurdo and the DOE NSA site, which revealed that roughly one quarter of observed supercooled layers are in a stable, non-turbulent atmospheric state. To our knowledge, this is the first demonstration that climate models probably require gravity wave parameterizations for not only cirrus ice formation (as quite widely recognized if not yet widely implemented), but also droplet activation in stable atmospheres. Plans already afoot to implement such a scheme for ice microphysics in ModelE3 have therefore been extended to apply to droplet activation, for which an AWARE case with gravity waves will be a future testbed. Meanwhile, ModelE3 SCM simulations of the AWARE LES case demonstrated that existing ModelE3 physics schemes (cloud and turbulence) are remarkably successful in developing and sustaining a snowing and drizzling cloud with an initially stable and later decoupled turbulent layer, as observed, when droplet number concentrations are similar to LES with mid-latitude aerosol and without gravity wave inputs (Fridlind et al., manuscript in preparation).

Work on the AWARE case and reading of existing satellite literature led the modeling team to focus on supercooled cloud-base precipitation as an observational target for model development. Using both AWARE and NSA data with a novel sounding-based approach to identify all the liquid layers in a column, Silber et al. (2021a) found that the great majority of supercooled clouds are precipitating from cloud base over both sites, primarily in the ice phase. Silber et al. (2021a) also reconciled very high precipitation occurrence from ground-based measurements with much lower reports from satellite observations by demonstrating the impact of reduced radar sensitivity on the ground-based data (vertical resolution was found to be not as important). In order to systematically evaluate ModelE3 (and other climate models), Silber et al. (2021b) developed a simulator tool (EMC^2) for use with ground-based lidar, radar, and sounding measurements. The tool also emulates the satellite view; training the simulator with the highly supercooled LES AWARE case provided a foundation for improving forward simulation of spaceborne lidar with ModelE3, as reported in GRL by Cesana et al. (2021). That paper demonstrated the importance of ice precipitation to robust comparison of supercooled cloud fraction with CALIPSO observations, as well cloud feedbacks. In follow-on work, we are applying EMC^2 to evaluate liquid cloud base precipitation properties over multiple ARM sites and deployments.

Finally, we used a one-dimensional modeling approach with size-resolved bin microphysics to work with the observational team to investigate the cause of unique multi-wavelenth radar signatures observed over McMurdo. We demonstrated that unique DWR features attributed to a very narrow size distribution could be attributable to two key elements: (i) nucleation of ice in a narrow vertical layer leading to a narrow initial size distribution, and (ii) growth and sedimentation of the narrow ice size distribution into a supercooled layer leading to vapor growth followed by riming in an atmosphere without turbulent motions, thus sustaining the narrowness of the initial size distribution. Results are in submission to ACPD (Tridon et al., submitted).

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