Riming-dependent Snowfall Rate and Ice Water Content Retrievals for W-band cloud radar

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Original Referee comments are in italic

> manuscript text is indented, with added text underlined and ~~removed text crossed out.~~

We would like to thank the reviewers for their helpful comments. We revised the manuscript and responded to all of the reviewers' comments.

Reviewer II

The paper presents the development of emperical IWC-Ze and SR-Ze relationships for obtaining snowfall rate and ice water content from W-band radar observations and accounting for the effects of riming. The work documents the performance of the relationships both when the normalized rime mass is known and when liquid water path is used as a proxy for rime mass. The normalized root-mean-square errors are somewhat large for small IWCs and SRs, but decrease as IWCs and SRs increase, giving performance generally better than a number of previously published studies.

The presentation of the work is clear and well organized. The conclusions are supported by the results. I have some requests for clarification or additional explanation that I consider mostly minor; see the comments below. I'm recommending acceptance with minor revisions.

My most significant concern is that it took a fair amount of examination of prior work (Seifert et al., 2019 and the earlier works by Maherndl et al.) to resolve in my mind the implications of changes in normalized rime mass. For example, does an increase in normalized rime mass mean that mass and D_max are unchanged,but that some of the mass is converted to lower-density rime mass? It would be helpful for the authors to provide a brief explanation to provide background for the readers, then allow them to consult the references if they desire a deeper understanding.

We thank the reviewer for the positive review and the constructive comments, which helped to improve the manuscript.

We added an additional explanation of the normalized rime mass M and its link to particle size.

> M is a quantitative measure of how heavily rimed an ice particle is with $M = 0$ meaning completely unrimed and $M \to 1$ meaning spherical graupel. M is not necessarily dependent on particle size. However, assuming a fixed amount of liquid water available for riming, larger particles will have lower M than smaller particles after riming (Maherndl et al., 2023).

Science and technical comments

L 21-22: Most gauges do not measure snowfall rate directly. Normally, they measure accumulation over a time interval, which is then used to compute mean liquid-equivalent snowfall rate over the time interval.

We agree and changed the sentence to:

> While gauges provide direct measurements of snowfall accumulation, which is used to compute SR, they are prone to large uncertainties (e.g., Saltikoff et al., 2015).

L 28-29: I don't think that W-band radars are commonly used for snowfall. There are complications introduced by attenuation and non-Rayleigh scattering by snow particles. For many operational applications, C- or S-band weather radars are the most commonly used for estimating snowfall rates, usually using empirical Ze-S relationships. Space-based operational missions like Global Precipitation Measurement and Tropical Rainfall Measurement Mission use Ku- and Ka-band radars, although they do suffer from a lack of the sensitivity needed for lighter precipitation. Research programs like CloudSat and US Department of Energy's Atmospheric Radiation Measurement do employ W-band and Ka-band radars which are used for snowfall retrieval, but W-band radars are probably the least common types used for snowfall.

We disagree when it comes to space-borne snowfall estimates. Until recently, CloudSat provided the reference for global snowfall estimates and EarthCare will likely fill that role. GPM does not cover polar regions in addition to the sensitivty issues you mentioned.

L 34-35: Do you have a reference for the information content of satellite observaions for snowfall?

Yes, we added a reference:

> Further, the information content of satellite observations is typically not sufficient to constrain the highly variable microphysical properties of snow and ice particles unambiguously (Wood, L'Ecuyer, 2021).

L 56-58: After reviewing Scarsi et al. (2024), I don't see any claims or documentation that the 800 km swath of WIVERN produces reduced uncertainty in polar snowfall estimates versus CloudSat. Please be more clear about what your are claiming here.

Apologies, we linked the wrong Scarsi et al. (2024) paper, we have updated the reference. WIVERN has a higher sampling frequency due to its 800 km swath as compared to the "pencil beam approach" from CloudSat. Scarsi et al. (2024) show that a higher sampling frequency does reduce uncertainty.

L 59-60: I'm concerned about this assertion since it seems at odds with what has been found for the scanning Ku- and Ka-band radars used by GPM (scattering from the beam side lobes causing a deeper blind zone at larger angles of incidence). See Kubota et al. (2016, JTECH, doi:10.1175/JTECH-D-15-0202.1). The Coppola et al. reference is not available for examination.

We updated the reference, which is now publicly available as preprint in EGUsphere:

> In addition, WIVERN's 42° angle of incidence results in a ~~thinner~~ smaller radar blind zone near the surface (especially over the ocean) ~~(Coppola et al., 2024)~~ (Coppola et al., 2025).

L 97-98: Do you have a reference for the statistical retrieval itself? Is this the LWP from the two-channel or from the three-channel radiometer? How was the Pluvio gauge fenced?

We used the ARM 3-channel microwave radiometer liquid water path and added in the text:

> We use additional data acquired by ARM of near-surface air temperature T, SR from a Pluvio weighing precipitation gauge and liquid water path (LWP). ~~The latterproduct~~ For the latter, we use the ARM 3-channel microwave radiometer LWP, which is derived from a site-specific statistical retrieval from microwave radiometer brightness temperature measurements.

The Pluvio gauge was located in a Low Porosity Double Fence as written in lines 373-374 (of the revised manuscript).

L 160: It seems rather arbitrary to remove light snowfall cases. What is the justification for doing this?

Under extremely light snowfall (corresponding to less than 0.1 mm/hr SR), random errors of the observed PSD are problematic. In addition, the matching between the in situ snowfall camera and the lowest radar range gate is prone to large uncertainty. For example, the radar might "miss" light snowfall that is measured by the in situ instrument. Additionally, light snowfall cases contribute less to total snowfall amounts.

L 173-174: When you say "horizontally aligned", do you mean perfectly horizontally aligned, or are the particle orientations allowed to vary randomly by some maximum angle relative to horizontal (i.e., 'flutter')? My experience with discrete dipole calculations indicates the first approach can overestimate backscatter cross-sections if the radar is vertically pointing. This may not be a significant concern with a 40-degree viewing angle, though.

The artificial particles are horizontally aligned and not fluttering. We used the Self-Similar Rayleigh Gans Approximation (SSRGA), to estimate radar backscattering cross-section. The parameterization of the SSRGA backscattering cross-section for rimed particles is described in Maherndl et al. (2023), where we evaluated the method against DDA.

L 180: Can you provide a reference for this assertion about the dominance of riming for particle mass?

Yes, we added two references:

> Because currently no particle classification product is available for all sites and mass-size parameter variability is rather dominated by riming than by particle shape (Maherndl et al., 2023; Mason et al., 2018), we assume a mixture of particle shapes (columns, dendrites, needles, plates, rosettes) and use the "mean" mass-size parameters, which are closest to the parameters for aggregates of plates.

L 219-224: So, to be sure that I understand, you compared the relationship between Ze and IWC for 90-degree observations from SAIL against the corresponding relationship derived for 40-degree observations from SAIL? And the m(D) parameters by which IWCs were determined were obtained by fitting modeled reflectivities (obtained from the observed PSDs) against the observed 40-degree slant path observed Ze?

Yes, we performed the M retrieval for 90-degree observations and 40-degree observations during scans at the SAIL site, calulated IWC and compared to Z_e (in the range gate closest to the in situ snowfall camera). We found a shift in Z_e, which we strongly assume is due to particle orientation. Yes, m(D) are obtained from fitting modeled reflectivities (from the observed PSDs) and observed reflectivities for the respective viewing angle, which is accounted for in the forward modeling.

L 232-249: There are a few things to clarify here. First, although the relationships given in (6), (7), (8), and (9) are general, is it your intention to fit these relationships using the 40-degree Ze observations? And I'm fairly certain the 'LWP' used here is the LWP measured in the vertical direction, but it would be helpful to explicitly say so. The reason to clarify this is that at least one of the DOE microwave radiometers (the two-channel) produces both a liquid water path in the zenith direction and a liquid water path that is along the line-of-sight path of the radiometer.

Yes, the intention is to use the 40-degree Z_e. We only use the lowest Z_e (closest to ground) so that we can compare to the ground-based in situ data. We do not look at the (slanted) Z_e column. LWP is taking vertical not slanted. We did not shift the time series because the averaging we do is sufficient, see the discussion in lines 168-171 (of the revised manuscript).

We have added the following:

> The reference IWC in $\mathrm{kgm^{-3}}$ and SR in liquid water equivalent $\mathrm{mmhr^{-1}}$ (Sect. 3.2) are related to the ~~equivalent~~ (40° slanted) radar reflectivity factor close to ground z_e in linear units $\mathrm{mm^6m^{-3}}$, ...

and

> Therefore, we also relate the reference IWC in $\mathrm{kgm^{-3}}$ and SR in liquid water

> equivalentmmhr^{-1} to z_e in mm^{6}m^{-3}, T in °C, and the vertical LWP in kgm^{-2}, ...

L 273-275, Figure 4: Distinct point shapes are not apparent, particularly in the locations where the scatter plot point density is high. Would 2D histograms be more useful for panels (a) and (c)? Also, in Figure 4, there are some interesting behaviors. In panel (a), if one follows a vertical, downward trajectory of constant Ze, normalized rime mass M increases while IWC decreases. It would be interesting to see what this means in terms of size distribution changes, but that is beyond the scope of this work.

Because we want to show M colorcoded and think this information is more important than the density of data points, we decided against 2D histograms.

Thank you for the comment about size distribution changes, this would indeed be interesting to study.

L 297-299: This explanation seems a bit simplistic. Could there not be differences versus particle habit assumptions or versus the population of PSDs used by Hogan et al. to produce their relationship? It's not apparent to me that this difference is attributable solely to the use of unrimed particles by Hogan et al.

We agree and changed the sentence to:

> This is likely in part due to Hogan et al. (2006) using mass-size parameters for unrimed particles in ~~there~~ their calculations of reference IWC. Differences in particle habit assumptions and PSD observations might also play a role.

L 314-317: At the SAIL site, it appears the LIMRAD94 was limited to a range of 2000m, or a height above ground of about 1300 m at the 40-degree observation angle. Similarly the maximum range was 2000m at Eriswil. The maximum heights for the RPG-FMCW-94-DP and JOYRAD-94 are not specified. For this WIVERN-like comparisons, did you simulate an atmospheric column? What were the depths of the columns and how did you treat 94-GHz attenuation? Also, how did you approximate the 1 km horizontal resolution using the ground-based observations? Please explain more about how the WIVERN observations are simulated from the ground observations. Finally, given the empirical nature of the retrieval, it is not clear how these uncertainties are introduced into the retrieval process and how their effects are evaluated. Please explain.

We approximate the WIVERN observations simply by regridding and averaging the ground-based radar data to the vertical resolution planned for WIVERN and applying noise to account for the expected measurement uncertainties. The relations are then only applied to reflectiviy data in the range bin closest to ground, so that we can use the ground in situ data as a reference. We assume WIVERN data to be corrected for gaseous attenuation. We did not look at higher altitudes because we lack reference data there. In the revised text, we added:

> To approximate (attenuation corrected) WIVERN Z_e observations, the high resolution, ground-based data from SAIL and the additional sites are downsampled to WIVERN geometry, i.e., a vertical resolution of about 580 m and a horizontal resolution of 1 km. We consider only the lowest grid point of the regridded Z_e (meaning the lowest about 580 m), which we use to compare to our reference IWC and SR. In addition, uncertainty estimates are applied to the regridded data to approximate WIVERN measurements. Uncertainties are applied in form of Gaussian noise and afterwards our relations are applied to the regridded and noisy data. Z_e uncertainties are derived based on simulations (Battaglia et al., 2024); for T an uncertainty of 2 K, and for LWP an uncertainty of 30 gm^{-2} are assumed. 30 gm^{-2} was chosen based on the maximum uncertainty of the retrievals from Ruiz-Donoso et al. (2020) and Billault-Roux, Berne (2021) (in mid- and high-latitudes) ...

L 323-326: See my previous comment regarding how the effects of uncertainties are evaluated.

See comment above.

L 356-360: Wind effects ('pumping') are probably the most significant source of error for heated Pluvio guages. Did you consider filtering out cases with high wind conditions to see if the validation results improved?

The in situ data is also less reliable under high wind conditions (Maahn et al., 2024). By applying the VISSS blowing snow filter (see VISSS processing library https://github.com/maahn/VISSSlib), high wind speed events are mostly filtered out.

L 380-383: See my earlier comment. At face value, increased riming of particles should increase IWC. But in this case, you are describing the changes given a constant Ze. So, what physical processes are happening if Ze is constant but riming increases and IWC decreases? It would be helpful to most readers to provide some insight here.

We were not talking about a physical process keeping Z_e constant here, but rather about a space of possibilities. At a given Z_e one particle population made up of heavily rimed particles has a lower IWC than another particle population made up of unrimed particles. This is due to enhanced scattering of the heavily rimed particles. We have changed to:

> For a ~~constant~~ given Z_e, ~~the IWC is generally lower as the ice and snow particles are~~ ice particle populations have a lower IWC the more heavily rimed they are due to the enhanced scattering of rimed particles (Fig. 4).

L 391-395: Se my earlier comment. More details are needed in the discussion section regarding how these WIVERN-like measurements were produced and how observational errors were propagated into the empirical retrieval.

See comment above.

Minor language corrections

L 40: Should be 'particle size distributions'.

L 58: Should be 'signficantly reducing the uncertainty'.

L 295: Should be 'site'.

L 298: Should be 'their'.

L 357: Should be 'HYY is operated as'.

Thank you, we corrected the language errors.