The following pages have versions of Sect. 5 submitted to AMT on 10/12/2023 and on 11/02/2023.

J.Snider

11/02/2023

Here is the version of Sect. 5 submitted to AMT 10/12/2023:

We have reported surface measurements of S and near-surface measurements of Z. The latter came from overflights of a ground site, where a precipitation gauge was operated, and were acquired using an airborne W-band radar. The values of Z were corrected for attenuation.

The reported S_{HP} / Z' pairs plot at or above the S-versus-Z best-fit line of PV11 (Fig. 12) and the minimum relative S difference (Table 1) is no larger than 0.3. The PV11 data came from airborne measurements of W-band reflectivity, acquired within ± 100 m of flight level, and from coincident measurements of snow particle imagery. PV11 used a density-size function and a fall speed-size function, and measurements (PSD and particle images) to calculate S for snow particles that were classified as both rimed crystals and graupel. This classification is also consistent with the particle imagery we have presented (Fig. 11).

We have documented a substantial difference in comparisons between our snowfall rates and reflectivity-dependent S values calculated using an upper-limit S/Z relationship for unrimed snow particles (Hiley et al. 2011). Here the minimum relative S differences are 0.7 and 1.0 for our two overflights and in a comparison to our measurements correspond to an underestimation of snowfall rate (Fig. 12). The relative differences are approximately a factor of two larger than the precision of our snowfall rate measurement. We also report a substantial difference, and S underestimation compared to our measurements (Fig. 12), for the comparison made to an S/Z relationship which assumes the snow particles are aggregates (Matrosov 2007). The snowfall rate underestimates obtained using both Hiley et al.'s and Matrosov's S/Z relationships (Fig. 12) are perhaps expected given that the density factored into those S/Z calculations is small compared to that for rimed snow particles. It is also expected that the larger density and spherical shape applied in the SSKB S/Z relationship contributed to the better agreement (minimum relative difference ~ 0.3) with our S_{HP} / Z' pairs. Our conclusion is that some snowfall retrievals (e.g., Hiley et al. 2011) will underestimate S for weather targets containing rimed snow particles. We also state that our conclusion is at odds with measurements and analysis in Falconi et al. Those researchers reported S/Z relationships for rimed snow particles which in instances with Z < 8 mm^6 m^{-3} plot below the upper-limit of Hiley et al. (Fig. 12). The consequence is that the minimum relative S difference in our comparison to Falconi et al. (assuming Falconi et al.'s heavily-rimed classification) is comparable to and larger than in our comparison to the Hiley et al.'s upper-limit S/Z relationship.

New research is needed to refine the S/Z relationship for rimed snow particles. This could be computational – e.g., investigation of the utility of parameterizing S in terms of both Z and density – or could be observational. Unlike the investigation of PV11, where only an airborne platform was employed, we have demonstrated that useful information can be obtained using coordinated ground-based and airborne systems. Another approach would be with only ground-based instrumentation. This would avoid some of the complications encountered in this study, including W-band attenuation and a reliance on particle imagery acquired aloft. A study with both ground-based and airborne systems would also be useful for understanding an S/Z mismatch apparent at Z < 8 mm^6 m^{-3}. Elements of the mismatch are the measurements reported here, PV11's best-fit line, and the measurement-based S/Z relationships reported by Falconi et al. (2018). These three research teams reported measurements relevant to the development of an S/Z relationship for rimed snow particles.

Here is the version of Sect. 5 submitted to AMT on 11/02/2023:

We have reported surface measurements of S and near-surface measurements of Z. The latter came from overflights of a ground site, where a precipitation gauge was operated, and were acquired using an airborne W-band radar. The values of Z were corrected for attenuation.

The reported S_{HP} / Z' pairs plot at or above the S-versus-Z best-fit line of PV11 (Fig. 12) and the minimum relative S difference (Table 1) is no larger than 0.3. The PV11 data came from airborne measurements of W-band reflectivity, acquired within ± 100 m of flight level, and from coincident measurements of snow particle imagery. PV11 used a density-size function, a fall speed-size function, and measurements (PSD and particle images) to calculate S for snow particles that were classified as both rimed crystals and graupel. This classification is also consistent with the particle imagery we have presented (Fig. 11).

We have documented a substantial difference in comparisons between our snowfall rate measurements and reflectivity-dependent snowfall rates calculated using an upper-limit S/Z relationship (Hiley et al. 2011). This S/Z relationship produces an underestimate of the snowfall rate (Fig. 12) when compared to our measurements. We also report substantial snowfall rate underestimates in comparisons of our measurements to the S/Z relationship developed by Matrosov (2007). The underestimates obtained using the Hiley et al. and Matrosov S/Z relationships are perhaps expected given that the density factored into those S/Z calculations is small compared to that for rimed snow particles. It is also expected that the larger density and spherical shape applied in the SSKB S/Z relationship contributed to the better agreement seen in the comparison of the SSKB relationship to our snowfall rate measurements. Our conclusion is that some snowfall retrievals (e.g., Hiley et al. 2011) will underestimate S for weather targets containing rimed snow particles. We also state that our conclusion is at odds with measurements and analysis in Falconi et al. Those researchers reported S/Z relationships for rimed snow particles which in instances with $Z < 8$ mm^6 m^{-3} plot below the upper-limit of Hiley et al. (Fig. 12). A consequence is that the minimum relative S differences in our comparison to Falconi et al. (assuming Falconi et al.'s heavily-rimed classification) is comparable to and larger than in our comparison to Hiley et al.'s upper-limit S/Z relationship (Table 1).

New research is needed to refine the S/Z relationship for rimed snow particles. This could be computational – e.g., investigation of the utility of parameterizing S in terms of both Z and density – or could be observational. Unlike the investigation of PV11, where only an airborne platform was employed, we have demonstrated that useful information can be obtained using coordinated ground-based and airborne systems. Provided all key measurements are acquired (S, PSD, particle imagery, and Z), another approach would be with only ground-based instrumentation. This would avoid some of the complications encountered in this study, including W-band attenuation and a reliance on particle imagery acquired aloft. A study with both ground-based and airborne systems would also be useful for understanding an S/Z mismatch apparent at $Z < 8$ mm^6 m^{-3}. Elements of the mismatch are the measurements reported here, PV11's best-fit line, and the measurement-based S/Z relationships reported by Falconi et al. (2018). These three research teams reported measurements relevant to the development of an S/Z relationship for rimed snow particles.