Does Snow Follow an $R - D_m$ Relationship?

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Motivation

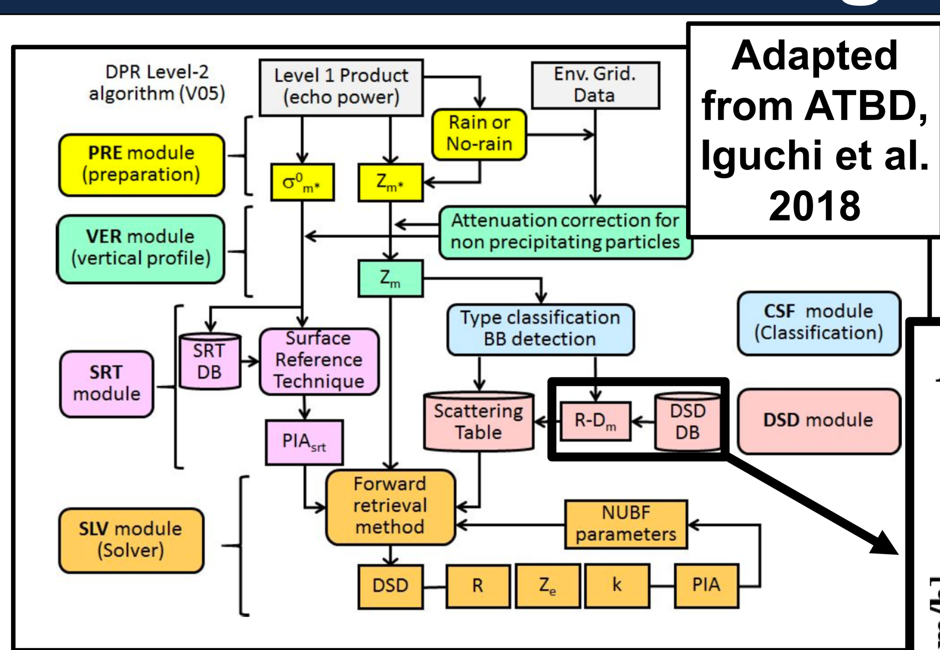
GPM-DPR estimates of snowfall rate are low

Skofronick-Jackson et al. (2019) showed that even considering the sampling differences between CloudSat and GPM-DPR, the DPR global average snowfall rate was ~ 47% lower than those retrieved from CloudSat

Petersen et al. (2019) showed that when compared to surface based radar estimations in Finland, GPM-DPR had a 55% low bias.

As a first investigation of where the low bias originates, we pose the question, "Does snow follow an $R - D_m$ relation?"

GPM-DPR algorithm V06



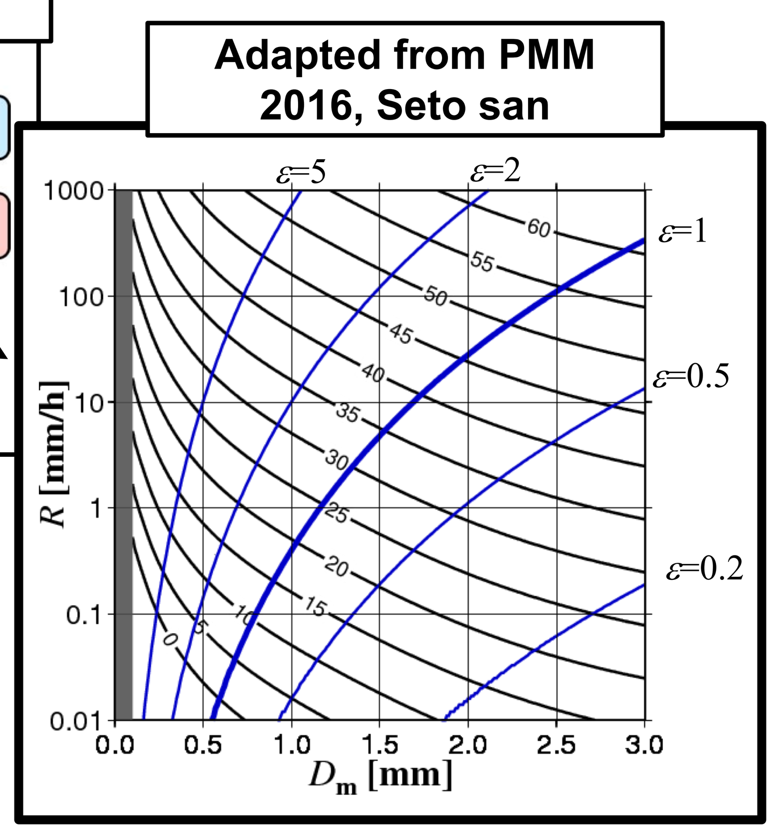


*Fig. 1: **(a)** Flowchart from the Algorithm Theoretical Basis Document (ATBD) showing the work flow in the GPM-DPR retrieval. The Drop Size Distribution DataBase (DSD DB) is outlined to show where part **b** fits into the flowchart. **(b)** R-Dm relationships used within the GPM-DPR retrieval adapted from Professor Seto san's presentation at PMM PSDWG meeting 2016 in Houston, TX*

- Since the release of V04 of the GPM-DPR data, the DSD module has changed to use an $R - D_m$ framework for retrievals
- The drop size distribution database (DSD DB), from which the R and D_m are retrieved, was created based on surface observations of rain
- This framework is used throughout the atmospheric column **regardless** of hydrometeor phase (see page 69, section 3.6.2-8 in ATDB)

Derivation of Liquid Equivalent D_m

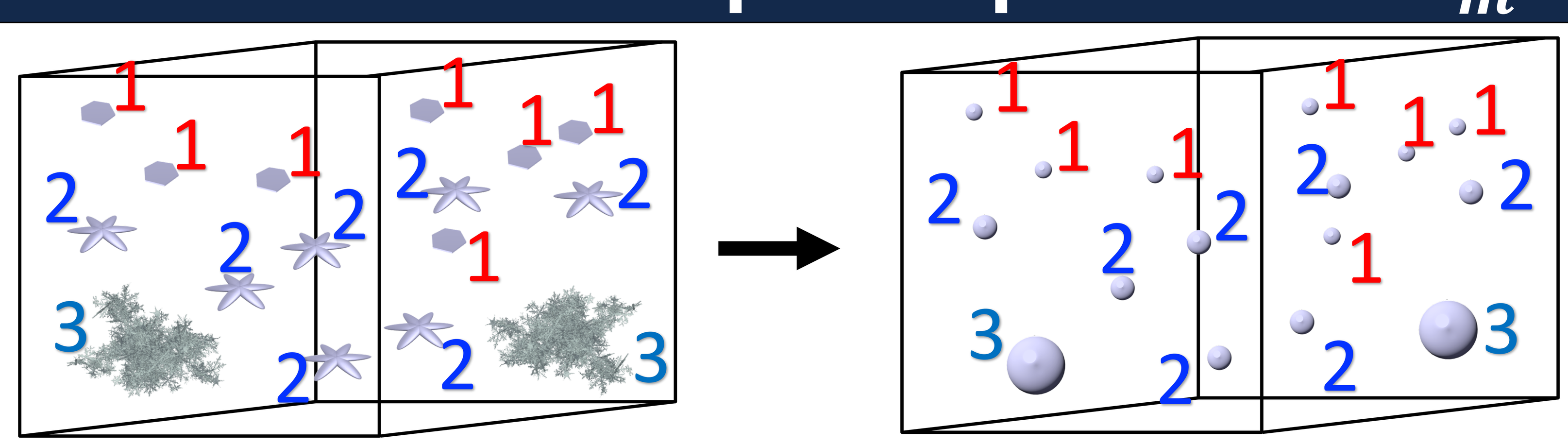


Fig. 2: A diagram to illustrate the hypothetical conversion of frozen particles (left) to a liquid equivalent particles (right). Numbers indicate the hypothetical bin number. Particle image renderings are adapted from the ARTS database manual: https://zenodo.org/record/1175573

$$D_m = \frac{\int m(D) D \, N(D) dD}{\int m(D) N(D) dD} \qquad D_{m_{melted}} = \frac{\int m(D) D_{melted} \, N(D) dD}{\int m(D) N(D) dD}$$

$$D_m = \frac{\sum_{i=0}^{n_{bins}} m(D_i) D_i \, N(D_i) dD_i}{\sum_{i=0}^{n_{bins}} m(D_i) N(D_i) dD_i} \qquad D_{m_{melted}} = \frac{\sum_{i=0}^{n_{bins}} m(D_i) D_{melted_i} \, N(D_i) dD_i}{\sum_{i=0}^{n_{bins}} m(D_i) N(D_i) dD_i}$$

- In order to compare the $R - D_m$ relations in the ATBD and those derived in snow, a liquid equivalent D_m needs to be calculated.
- We assume all particles in each bin are of the same density/type, then $N(D_i) dD_i = N(D_{melted_i}) dD_{melted_i}$. This preserves mass content and total number concentration

BAECC 2014 – 2015

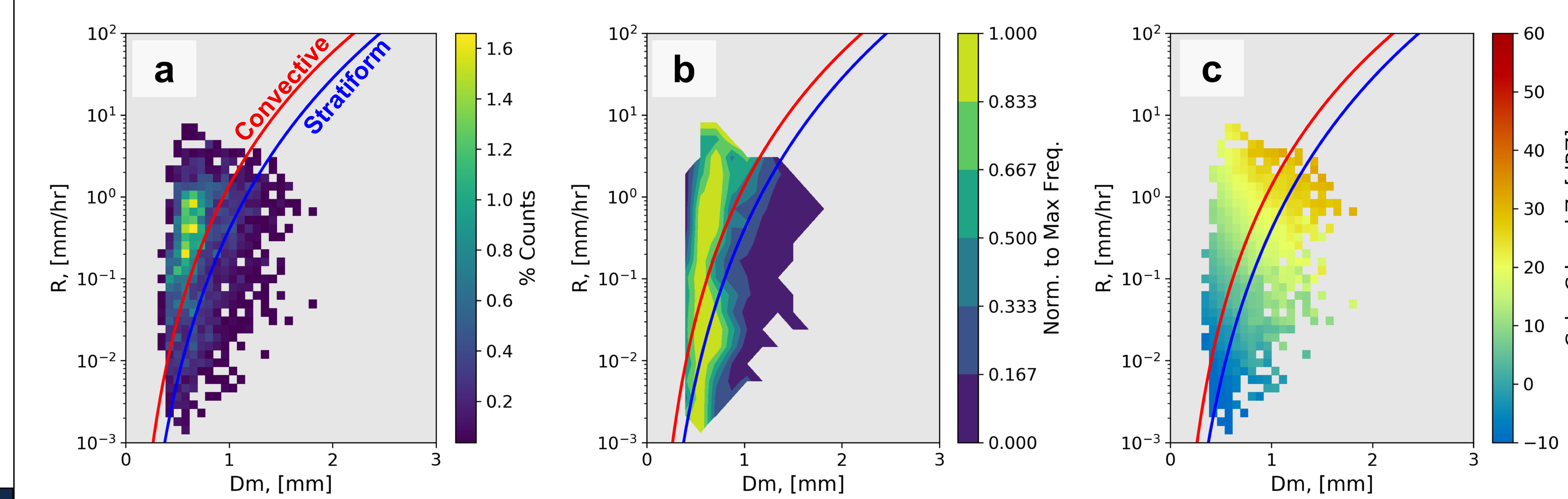


*Fig. 3: Surface PIP **snow** observations (5-min) from Finland framed in the $R - D_m$ space. R and D_m are in liquid equivalent. The solid blue and red lines correspond to the default stratiform and convective relationships in the GPM-DPR algorithm if $\epsilon = 1$ **(a)** 2D histogram normalized to the total number of observations (n= 3020) **(b)** Contoured 2D histogram (same as **a**) but normalized to the mode in each vertical bin as opposed to the total number of observations **(c)** Same 2D histogram as **a**, but now colored by the bin median C-band reflectivity. C-band reflectivity is calculated using the same expression as in von Lerber et al. (2017).*

- Surface measurements of snowfall from southern Finland (61.485°N, 24.287°E) were collected by a Precipitation Imaging Package (PIP) between February 2014 – April 2015
- Bin-resolved mass for each PSD was retrieved following von Lerber et al. (2017) technique which allowed for the calculation of the liquid equivalent D_m and R.
- Figure 3 shows that snow PSDs over southern Finland tend to deviate from the prescribed relations, but still have increasing Z as R and D_m increase concurrently.

Marquette, MI 2015 – 2018

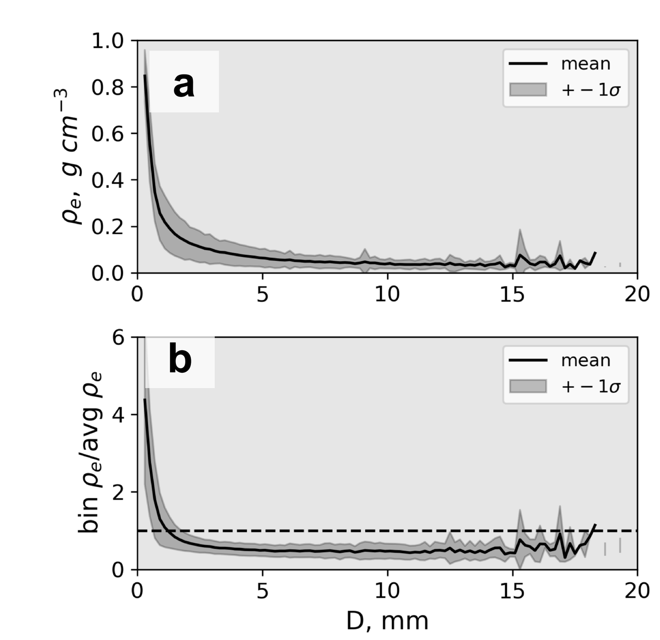


*Fig. 4: Effective density (ρ_e) adjustment. **(a)** Bin-wise ρ_e calculated from the retrieved masses from the PIP data in BAECC 2014-2015. **(b)** Ratio of the bin ρ_e to the total PSD average ρ_e.*

- Surface measurements of snowfall in Marquette, Michigan (46.53 °N, 87.55 °W) have been taken every winter since 2014 using the PIP
- The bin-resolved mass is not readily available for this dataset, but an estimate of the 1-min PSD average effective density (ρ_e) is provided for data extending back to 2015.
- The ρ_e is estimated using an empirical model relating the particle size and terminal fall speed (personal communication: Claire Pettersen)
- Using the relationship of PSD average ρ_e and that of the bin-wise ρ_e from the BAECC 2014-2015 data, a bin-resolved mass can be diagnosed for all PSDs collected (Fig. 4)

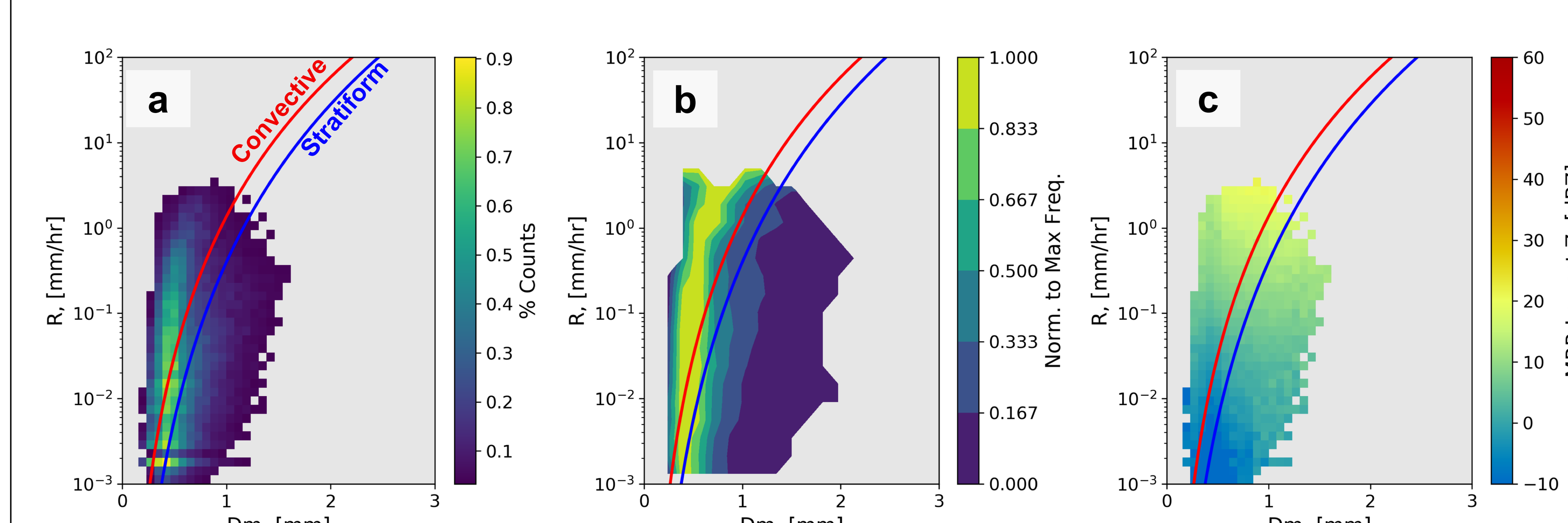


Fig. 5: As in Fig. 3, but now for 1-min PIP observations taken in Marquette, Michigan between 2015 and 2018. (n = 91,139)

- After diagnosing the bin resolved mass as explained above, the Marquette data can be framed similarly to the BAECC observations
- Although the confidence of bin resolved mass is lower for the Marquette data compared to the BAECC data, Fig 5a,b shows that the Marquette data **also deviates** from the prescribed $R - D_m$ relation
- Collocated MRR data demonstrate a consistent increase with Z away from the origin

Comparison to Rain

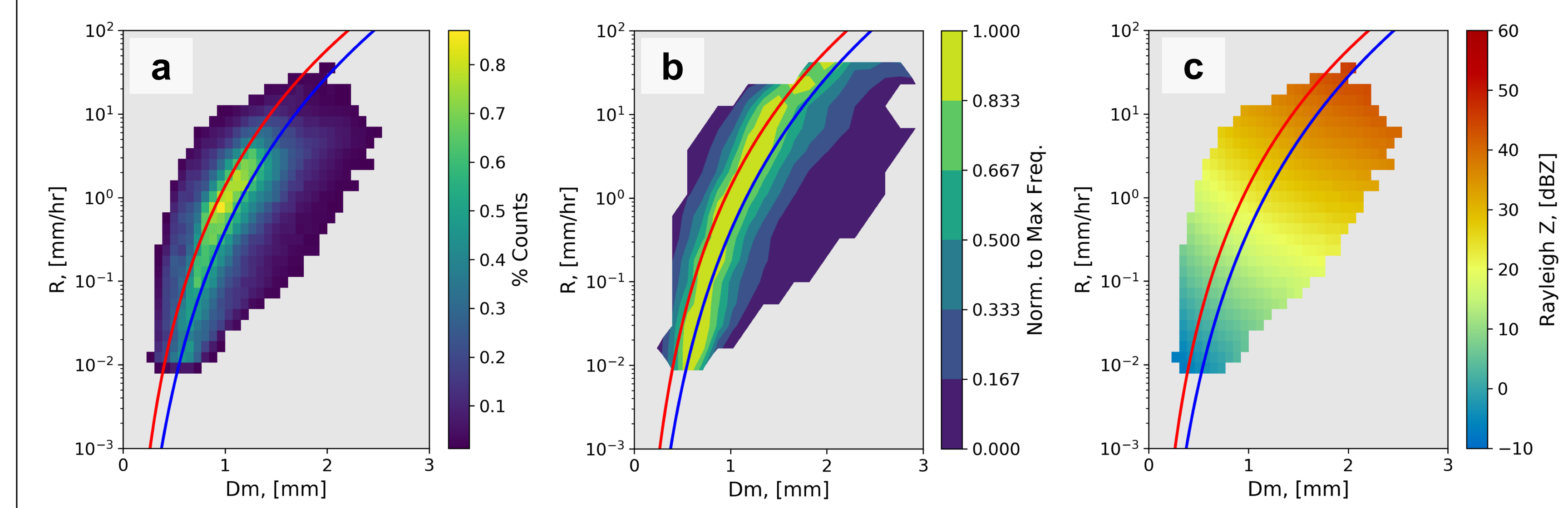


*Fig. 6: As in Fig. 3, but now using 1-min **rain** observations using the 2-dimensional video dendrometers (2DVD) located at NASA GV campaigns in chronological order; LPVEX (Southern Finland) , MC3E (Oklahoma, USA) , IFloodS (Iowa, USA), IPHEX (North Carolina, USA), OLYMPEX (Coastal Washington, USA) and Wallops (Coastal Maryland, USA). n = 243,026*

- Fig. 6 shows that NASA GV 2DVD rain data are consistent with the prescribed relations, shifting from the stratiform curve (blue) to the convective curve (red) as R increases

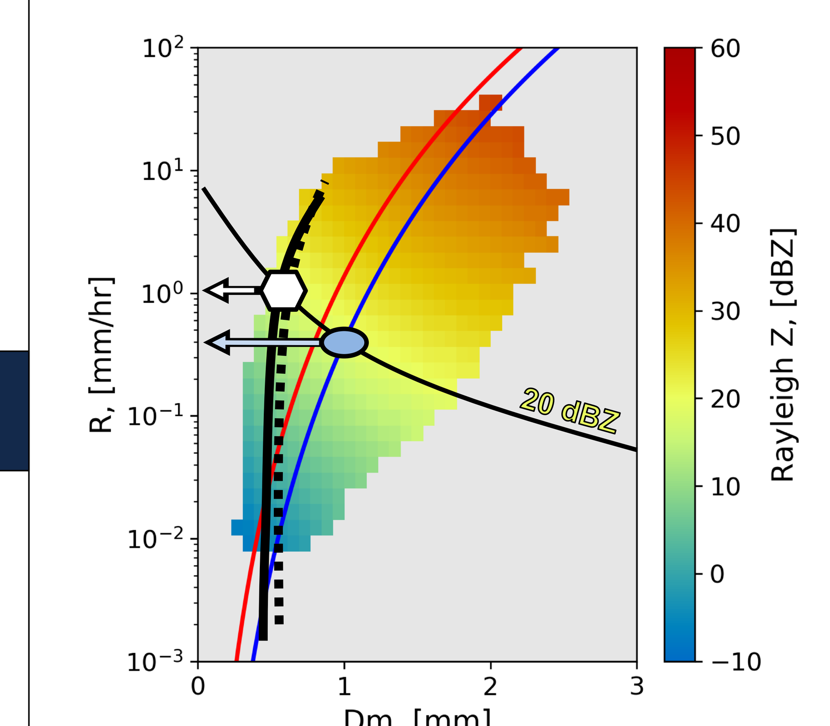


Fig. 7: Considering an example retrieval for a radar gate with a 20 dBZ echo. Shaded grid is the same as Fig. 6c. Thick black lines are new relations drawn from Fig. 3b (dotted) and Fig. 5b (dashed). Hexagon is the result using the new relations, oval is the old relations.

- For a given reflectivity, say 20 dBZ, if the prescribed relations are used, it would result in 0.4 mm hr $^{-1}$, while if a new prescribed relation based off of the snow PSDs would results in 1 mm hr $^{-1}$.
- This difference is ~50% bias, which is consistent with the literature reported estimates for how low GPM-DPR estimates are
- Better agreement is found with smaller R and D_m

Conclusions

1) Ground based snow PSDs suggest that the $R - D_m$ for rain does not apply well for snow.

2) Using the rain relation as opposed to the snow relation would result in a 50% error for a radar echo of 20 dBZ.

References

Iguchi, T., Seto, S., Meneghini, R., Yoshida, N., Awaka, J., Le, M., Chandrasekar, V., Brodzik, S. and Kubota, T. 2018: GPM/DPR Level-2 algorithm theoretical basis document. Available from: https://pps.gsfc.nasa.gov/Documents/ATBD_DPR_201811_with_Appendix3b.pdf

Petersen, W., Pettersen, C., Kirstetter, P., Moisseev, D, von Lerber, A., Kulie, M., Marks, D., Tokay, A., Wolff, D. and Hudak, D. 2019: Translating the physics of snowfall to radar-based validation of GPM. Available from: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20190026609.pdf

Skofronick-Jackson, G., Kulie, M., Milani, L., Munchak, S. J., Wood, N. and Levizzani, V. 2019: Satellite estimation of falling snow: A global precipitation measurement (GPM) core observatory perspective. Journal of Applied Meteorology and Climatology, 58, 1429 – 1448.

von Lerber, A., Moisseev, D., Bliven, L., Petersen, W., Harri, A-M. and Chandrasekar V. 2017: Microphysical properties of snow and their link to Ze–S relations during BAECC 2014. *Journal of Applied Meteorology and Climatology*, 56, 1561 – 1582.

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