Utilizing Space-borne Radars to Retrieve Dry Snowfall

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I. Introduction

CloudSat's 94 GHz Cloud Profiling Radar (CPR) has provided the first true global snowfall measurements using space-borne radar as demonstrated by Liu (2008a). This study (Kulie and Bennartz 2009) provides a slightly different perspective of global snowfall and utilizes CPR snowfall observations to calculate proxy Global Precipitation Measurement (GPM) Dual-frequency Precipitation Radar (DPR) observations at 13.6 and 35 GHz. The following questions are explored:

1. What are the characteristic reflectivity and snowfall rate distributions at 94, 35, and 13.6 GHz both globally and regionally?
2. What is the sensitivity of retrieved snowfall rates to the assumed ice particle model?
3. What are the potential implications for GPM?
4. What other factors affect our results?

II. Methodology

1. **A near-surface snowfall dataset was compiled using the following criteria:**
   - Observations between +/- 30-75º were only considered from 7/06-7/07.
   - ECWMF-derived surface temperature of 0º or less (dry snowfall).
   - To help eliminate ground clutter:
     - ➢ Data bins at ~1.3 km AGL were used as "near-surface" values.
     - ➢ Near-surface reflectivity > -15 dBZ with vertical structure of ~1 km to be included in the database.
   - Dataset comprised of almost 5 million observations
     - ➢ 3% of total CPR observations within specified latitude belts
     - ➢ 13% of total sub-zero ECMWF observations
2. **Convert reflectivity (*Z*) to snowfall rate (*S*) using the following components:**
   - Define a set of snowfall rates a priori.
   - Derive the ice PSD for each snowfall rate using Field et al. (2005) ice PSD moment conversion scheme.
     - ➢ Assume mass- and fall speed-particle size relationships appropriate for aggregates.
   - Calculate *Z* by integrating over the PSD using backscatter coefficient data using spherical (Mie) or non-spherical (DDA) ice particle models.
   - 3 particular ice particle models are chosen to demonstrate sensitivity **(Fig. 1)**.
     - ➢ Hong (2007) aggregates (HA). **Red** line in Fig. 1.
     - ➢ Liu (2008b) 3-bullet rosette (LR3). **Black** line in Fig. 1.
     - ➢ Surussavadee and Staelin (2008) snow (SS). **Purple** line in Fig. 1.
3. **Derive *Z-S* relationships for different frequencies using power law fits (Fig. 2).**
   - Decent fits for each shape with relatively small relative errors due to fitting procedure.
   - For a given *S*, ice particle shape exerts a large influence on derived *Z*.
     - ➢ E.g., for *S*=1.0 mm h^{-1}, possible reflectivity range exceeds 10 dB.
   - Sample *Z-S* relationships For the LR3 shape:
     - ➢ 94 GHz: $Z = 13.2\ S^{1.4}$
     - ➢ 35 GHz: $Z = 24.0\ S^{1.5}$
     - ➢ 13.6 GHZ: $Z = 34.6\ S^{1.6}$

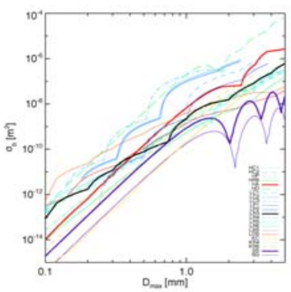


Fig 1: Backscattering coefficient [m^2] at 94 GHz versus maximum particle dimension [mm] for various frozen particle models. The shapes used in this study – LR3 (black), HA (red), and SS (purple) - are indicated by the thick, solid lines.

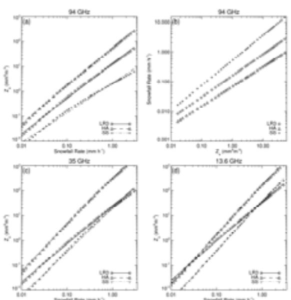
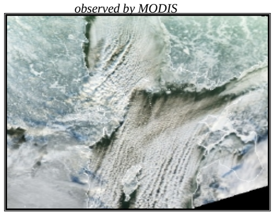
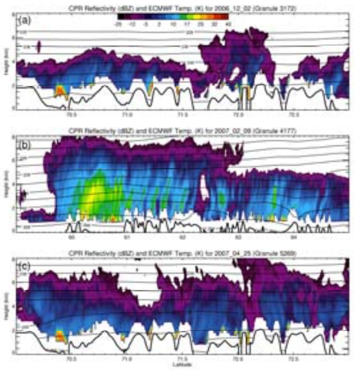


Fig 2: (a) Z [mm^6 m^{-3}] as a function of S [mm h^{-1}], at 94 GHz for the three different ice particle models highlighted in Fig. 1 – LR3 (diamonds), HA (triangles), and SS (crosses). Best-fit lines using the Z_e-S relationships are also indicated through the data points. (b) Same as (a), but for S as a function of Z_e (using the Z_e-S relationships from Table 1) at 94 GHz. (c) Same as (a), but for 35 GHz. (d) Same as (a), but for 13.6 GHz.

Lake-induced snowfall over the Baltic Sea as observed by MODIS



CloudSat (JPL Website)



CPR snowfall observations over Greenland

III. Global Results

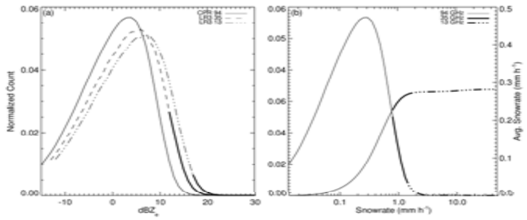


Fig 3: (a) Radar reflectivity factor histograms in 1 dBZ$_e$ bins for observed CloudSat CPR snowfall events (solid line) and calculated proxy radar reflectivities for 35 GHz (dash) and 13.6 GHz (dash-dot) using the LR3 Z_e-S relationship. The thick solid line on the 35 and 13.6 GHz histograms indicates the reflectivity bins that exceed the proposed minimum detectable signal (MDS) of the GPM DPR for each frequency. (b) Conditional snowfall rate histograms (left axis) and average conditional snowfall rate cumulative distribution function (right axis). The thick solid and dash-dot line on each curve represents the snowfall rate threshold corresponding to a MDS of 12 and 17 dBZ$_e$, respectively.

1. **CPR distribution results (Fig. 3)**
   - 94 GHz distribution peaks near 3 to 4 dBZ.
   - 94% of all CPR dry snowfall reflectivities are less than 10 dBZ.
   - Globally averaged conditional snowfall rate ~0.3 mm h^{-1}, but large potential uncertainties due to ice particle model (e.g., 0.1 - 1.0 mm h^{-1} for HA and SS shapes)
2. **Implications for GPM**
   - Light snowfall dominates globally. Detection difficulties for GPM DPR?
   - 35/13.6 GHz distributions peak near 6/7 dBZ, respectively.
   - Assuming 12/17 dBZ MDS, global snowfall detection efficacy is ~7/1%.
   - From a snowfall accumulation standpoint, detection efficacy is ~17/4%.
   - These results depend strongly on ice particle model.
   - CPR results provide valuable information about the lower end of the snowfall rate spectrum that may not be detected by GPM DPR.
3. **Sensitivity to vertical continuity threshold (Fig. 4)**
   - Reducing or eliminating vertical continuity threshold:
     - ➢ Greatly increases snowfall frequency of occurrence.
     - ➢ Increases ground clutter contamination (see secondary peak in reflectivity distribution in Fig. 4b).
   - Are legitimate shallow snowfall events missed in our dataset? These events can contribute significant amounts to global snowfall (not shown).
   - Cost-benefit analysis necessary for using this threshold. See Hiley et al. poster.

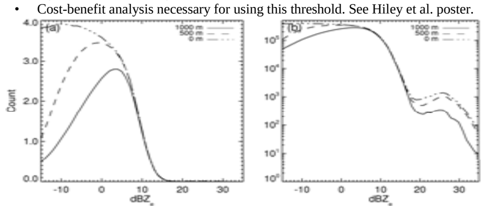


Fig 4: (a) Same as Fig. 3, but for different vertical continuity thresholds (thickness of required minimum reflectivity to be included in the snowfall dataset). (b) Same as (a), but in a logarithmic scale.

IV. Regional Results

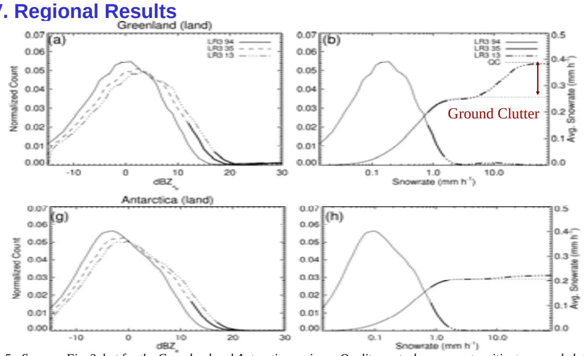


Fig 5: Same as Fig. 3, but for the Greenland and Antarctica regions. Quality control measures to mitigate ground clutter are also shown in the snowfall rate plot (QC).

1. **Greenland**
   - Light reflectivities and snowfall rates commonly occur over Greenland.
   - Expected DPR detection efficacy of ~7/2% for reflectivity and ~22/7% for accumulation.
   - Ground clutter contamination has strong effect on results (Fig. 5b)
     - ➢ Examples of Greenland snowfall cases also shown as the centerpiece figure. Ground clutter obvious in highly structured terrain.
     - ➢ Rudimentary quality control by using 8th CPR data bin AGL as near-surface reflectivity eliminates the excessive snowfall accumulation artifact at higher snowfall rates associated with ground clutter.
     - ➢ Is 8th CPR data bin AGL representative of surface snowfall?
2. **Antarctica**
   - Reflectivity and snowfall rate distribution peaks at much lower levels than Greenland.
   - Expected DPR detection efficacy of ~5/1% for reflectivity and ~16/4% for accumulation.
3. **North-Central Russia (not shown)**
   - Similar average conditional snowfall rate as Antarctica, but much different distribution.
   - DPR detection efficacy of ~2/0.2% for reflectivity and ~6/0.5% for accumulation.

V. Further Questions/Future Work

1. **Dry snowfall assumption valid?**
   - Ice particle models probably not valid for rimed snow
   - Passive microwave observations can help determine typical cloud liquid water associated with snowfall (over ocean only). Regional trends undoubtedly exist where cloud liquid water is climatologically important (see Hiley et al. poster).
2. **Near-surface reflectivity assumption valid?**
   - Better relationships between the near-surface reflectivity and actual surface reflectivity need to be developed (e.g. accounting for evaporation, cloud vs. accumulating snowfall, etc.)
3. **Attenuation effects?**
   - Attenuation effects are not accounted for in the current study and assumed to be negligible for the majority of light snowfall cases.
   - Attenuation is probably not negligible for heavier snowfall, especially associated with significant cloud liquid water content.
   - See Hiley et al. poster for more details.
4. **Multiple scattering effects?**
5. **Ground validtion.**
6. **Link these results to coincident passive microwave observations.**

References

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