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Detectability of Falling Snow with NASA CloudSat: Evaluation from NOAA/NSSL Ground-Radar-Based National Multi-sensor Mosaic QPE (NMQ) System

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Abstract

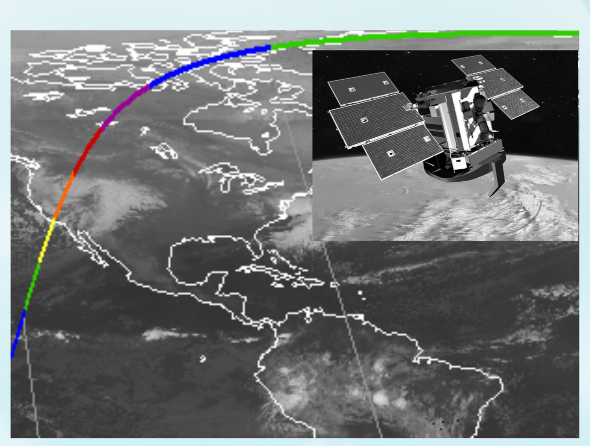
Snowfall represents a predominant portion of precipitation at mid- and high-latitude regions and greatly contributes to regional atmospheric and terrestrial water budgets. Accurate detection and estimation of snowfall is much desirable by various applications in meteorology, hydrology, and climatology. Nowadays, remote sensing has been a major approach for monitoring the regional and global precipitation. A state-of-the-art instrument is the first spaceborne cloud radar, Cloud Profiling Radar (CPR) onboard NASA's CloudSat satellite (http://cloudsat.atmos.colostate.edu/). CPR works at W-band (94 GHz) and provides good sensitivity for measuring the vertical structure of cloud liquid/solid water distribution. Combined with CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization) that is onboard NASA's CALIPSO satellite, CPR has proven to be capable of identifying and retrieving the snowfall.

Verification, refinement, and integration of spaceborne snowfall products require trustworthy ground-based dataset. Routine observations of snowfall have so far mostly been restricted to limited stations, with spotty spatial distribution and inconsistent duration of data record. The National Mosaic and Multi-sensor QPE (NMQ or Q2: http://nmq.ou.edu) system, developed by NOAA/NSSL and University of Oklahoma (OU), provides CONUS-wide high-resolution (5min/1km) QPE products, including the detection of falling snow. With appropriate data quality control by the radar quality index (RQI), NMQ/Q2 is regarded as an ideal, independent source for the validation of spaceborne products. NMQ/Q2 has been refined to the new Multi-Radar Multi-Sensor System (MRMS) since the summer of 2013.

The current study evaluates CloudSat-CPR's detectability of falling snow using NMQ-Q2 snowfall products (i.e., solid snowfall precipitation identification) over the CONUS. We have applied CloudSat geometric profile data (2B-GEOPROF) and snowfall-profiling data (2C-SNOW-PROFILE). Considering the difference in spatiotemporal resolution and grid consistency, we have also applied suitable interpolation and downscale methods to match CloudSat and Q2 data pairs. The evaluation results show the great potential of W-band cloud radar in detecting the falling snow. The detectability is also affected by the storm type and precipitation intensity. Further enhancement on the snow detection can be expected by incorporating the ground-radar-based NMQ products into spaceborne cloud radar observations.

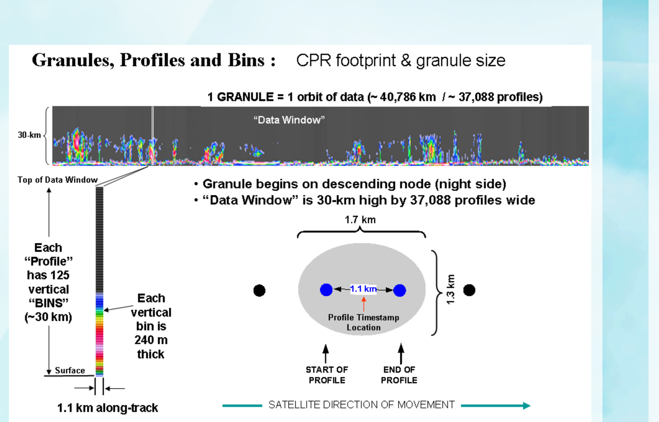
Platforms

1. CloudSat-CPR



- CPR is more than 1,000 times more sensitive than existing weather radar.
- CPR can "see" inside clouds to determine how much water and/or ice is inside.
- CPR provides vertical structure of clouds and rain from space
- CPR produces new meteorological data types including cloud-layer thickness, cloud top and base altitudes, and cloud water and ice content.

- *Nominal Frequency:* ***94 GHz***
- *Minimum Detectable Z:* *< -26 dBZ*
- *Pulse Width* *3.3 μsec*
- *Data Window:* *0-25 km*
- *Antenna Size:* *1.85 m*
- *Integration Time: 0.16 sec*
- *Nadir Angle (since 15 Aug 2006): 0.16°*
- *Vertical Resolution:* ***500 m***
- *Cross-track Resolution:* ***1.3 km***
- *Along-track Resolution:* ***1.7 km***
- *Sample Rate:* *0.16 sec/profile*
- *Along-track Velocity:* *7 km/sec*



2. NMQ/MRMS

- An operational, multi-radar, multi-sensor system built upon the CRAFT data network, providing real-time, CONUS-wide, high quality (5min/1km) radar and precipitation products such as hybrid scan reflectivity, precipitation type and rate.

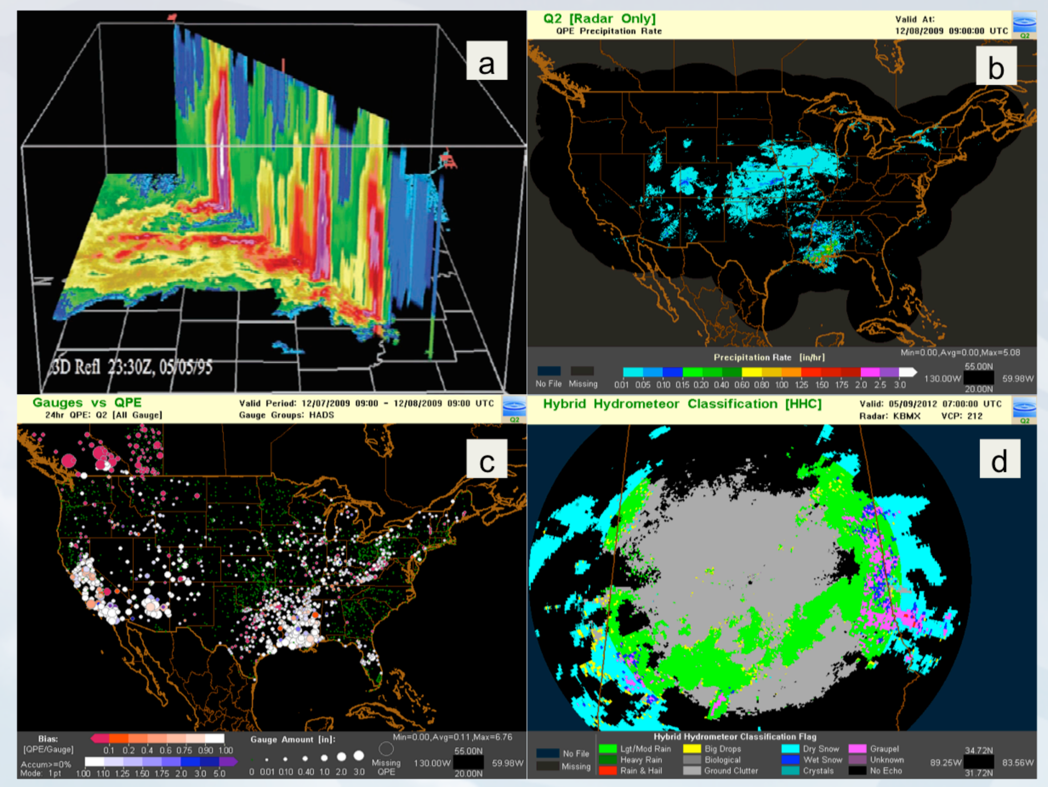
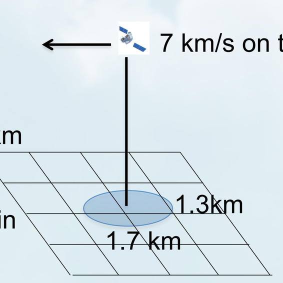


Fig. 1 (a) horizontal and vertical cross sections from NMQ-Q2 3D reflectivity mosaic; (b) NMQ-Q2 precipitation rates; (c) spatial bias distribution based on gauge measurements; (d) research product in NMQ-Q3: polarimetric hydrometeor classification.

Data Matching and Statistics

1. Datasets and matching

- NMQ/Precipitation Type/Phase
- NMQ/Precipitation Rate
- CloudSat/2B-GEOPROF
- CloudSat/2C-SNOW-PROFILE
- Time period (1/1/2009-3/26/2011)
- Found 413202 data pairs containing snow info.



NMQ and CloudSat data matching—find the NMQ data with the nearest location and time to each profile of CloudSat.

2. Data pair statistics

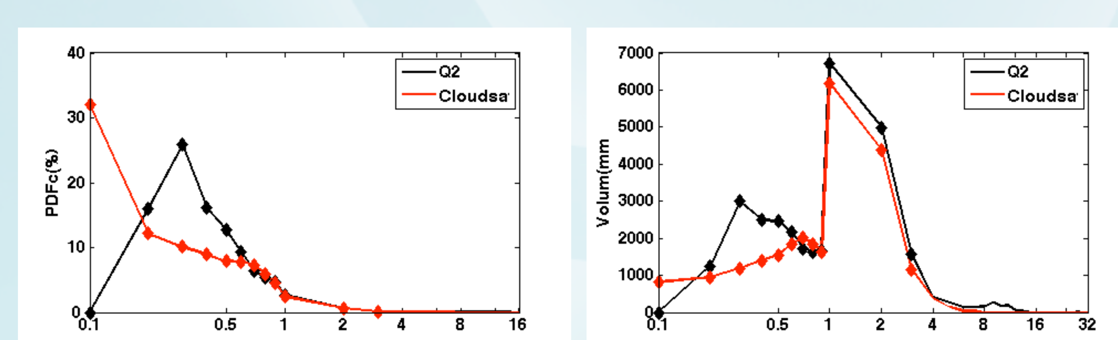


Fig. 2 Probability density function (PDF) of snowfall detection (left) and distribution of precipitation volume (right) in terms of equivalent liquid precipitation rate.

As the left figure shows, the NEXRAD radar generally under-detects the weak precipitation (~0.1 mm/h) while CPR has a much better sensitivity to detect the light snow. For heavier snowfall, both NEXRAD radar and CPR have a similar detectability. The right figure, which shows the precipitation volume, also support this result. CPR generally have underestimated snowfall for moderate and heavy snow. The underestimation of very heavy snow (e.g., >4 mm/h) is likely due to the insufficient correction of signal attenuation in W-band frequency.

Analysis Results

1. Detectability of CloudSat

This study uses the NMQ precipitation phase as the reference to evaluate the detection of snowfall by CloudSat. As the POD and FAR figures show, CouldSat can well detect the weak snowfall echoes (high POD and low FAR) as far as NEXRAD radar can detect them. However,

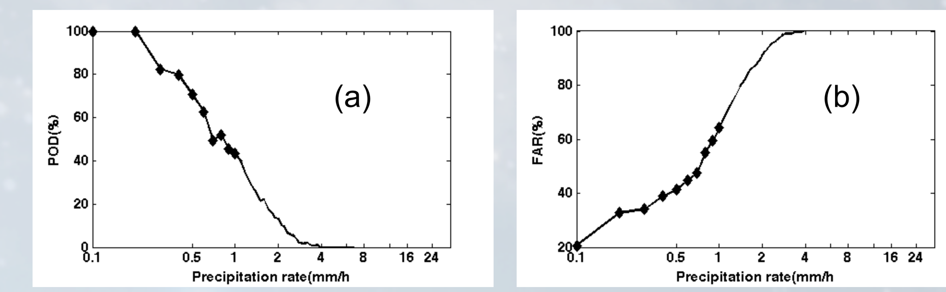


Fig. 3 (a) POD and (b) FAR of CloudSat snowfall detection in terms of NMQ snowfall rate. The rate in x-axis indicates the POD/FAR statistics are computed for all the data with the precipitation rate greater than the given rate.

when snowfall gets heavier, the detectability of CloudSat will decreases. This statement is based on the assumption that NMQ's snow detection/estimation represents the ground truth. Uncertainty may be introduced by the unreliability of NMQ products in Western US, where terrain effect might degrade the QPE results.

The following example shows the snowfall estimation by NMQ and CloudSat, which give consistent results.

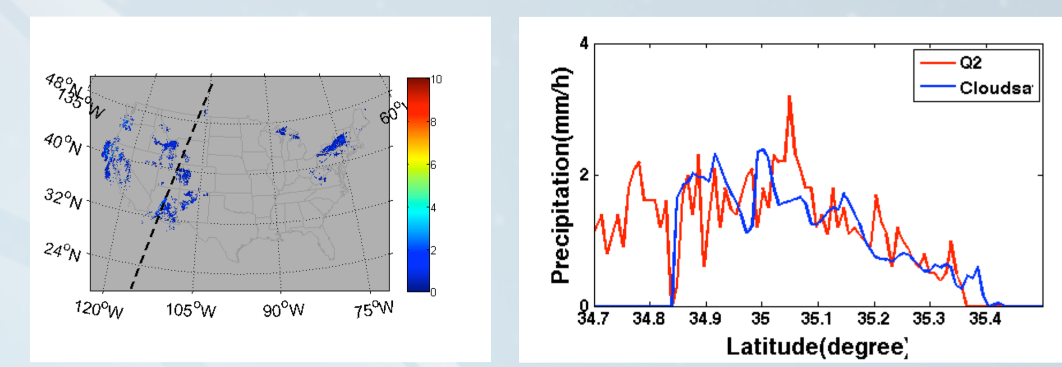
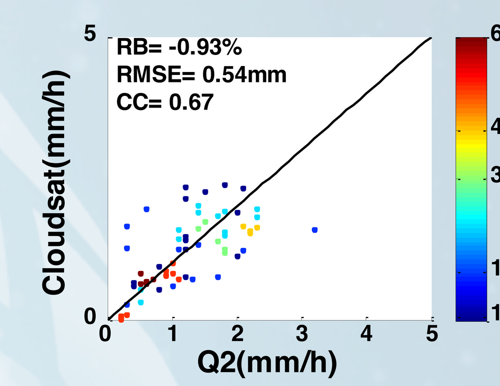


Fig. 4 NMQ precipitation rate overlapped with CloudSat track (left) and comparison of snowfall rate of NMQ and CloudSat (right) for 01/11/2010 storm.

- The scatter plot (right-side) shows the consistent measurements of snowfall by S-band and W-band radars, demonstrating CloudSat's capability of snowfall detection and retrieval.



2. Potential deficiency of CloudSat

The CloudSat snowfall detection/retrieval might be degraded by (1) the limitation in near-surface surveillance and (2) the insufficient correction of precipitation attenuation. The following cases show some examples.

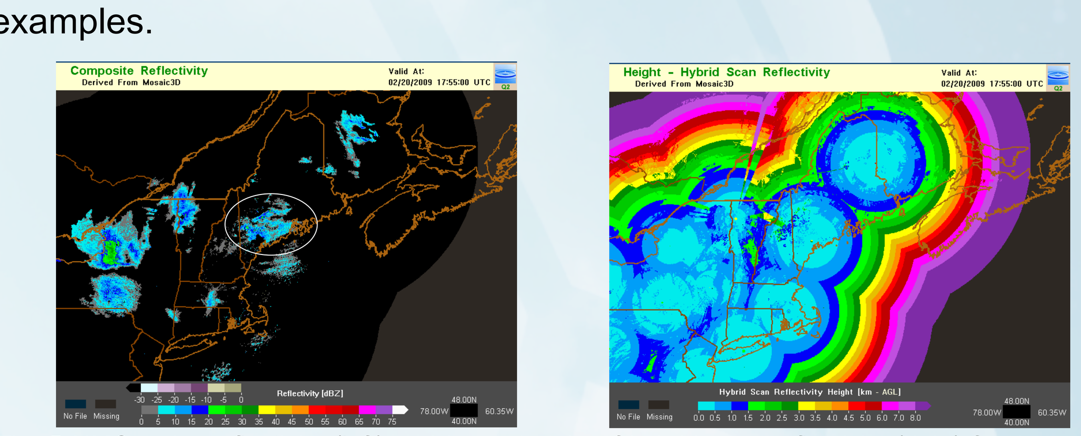
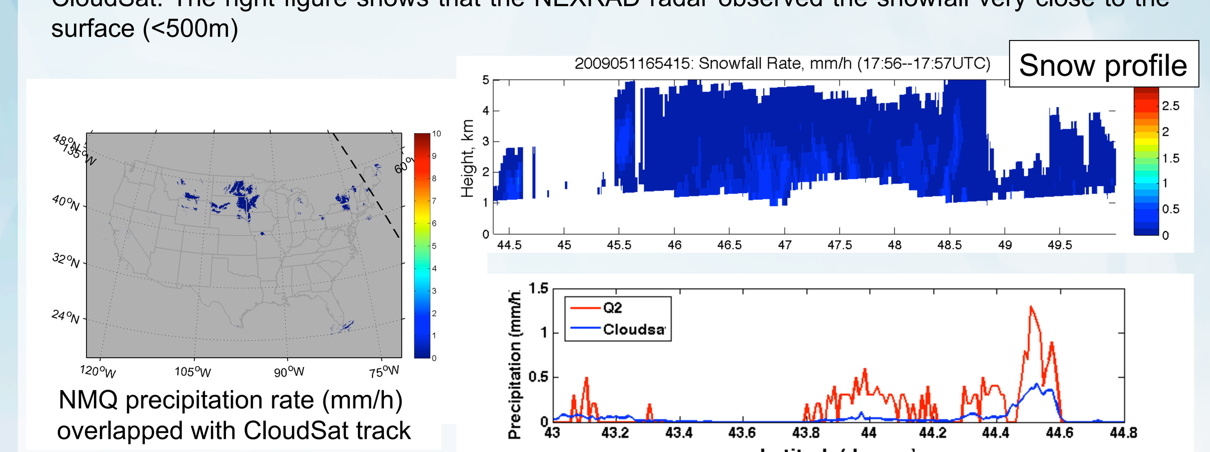
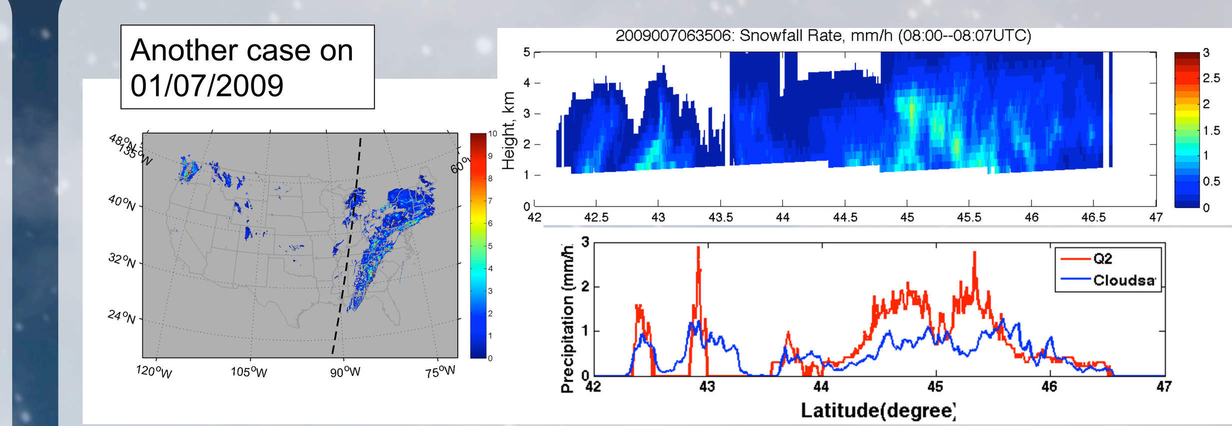


Fig. 5 NMQ radar reflectivity (left) and beam height of hybrid scan reflectivity (right) for the snow storm on 02/20/2009. The storms cells shown in the reflectivity figure have all been identified as solid precipitation. The enclosed region by the whit curve indicates the snow cell scanned by CloudSat. The right figure shows that the NEXRAD radar observed the snowfall very close to the surface (<500m)



NMQ precipitation rate (mm/h) overlapped with CloudSat track

Another case on 01/07/2009



These two case show that CloudSat well catch the temporal variation of snowfall as measured by NEXRAD radar although their snowfall retrievals tend to be underestimation. The reason is likely due to the fact that NEXRAD radars have a better capability in low-level atmosphere surveillance at the near radar range (e.g., <50km) while CloudSat may observe the upper level atmosphere than NEXRAD radars. The precipitation attenuation also contributes to the snowfall underestimation. The following case shows the effect of attenuation from heavy snowfall on CloudSat snowfall detection and retrieval.

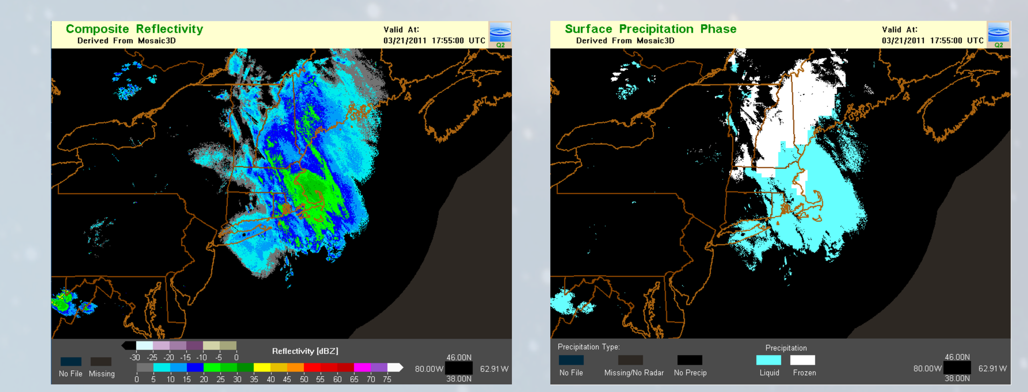
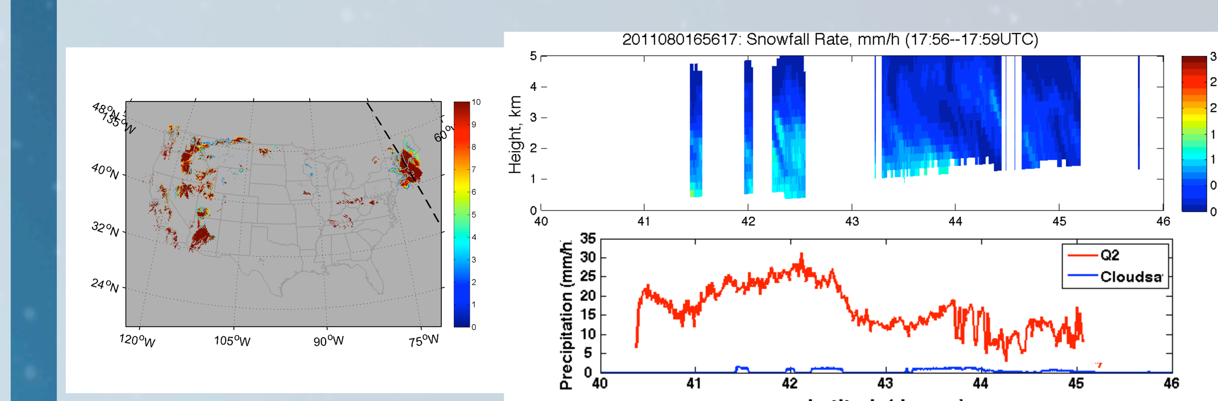


Fig.6 NMQ radar reflectivity (left) and surface precipitation phase (right) for 03/21/2011 snow storm. The reflectivity (~15 dBZ) and classification result clearly show the heavy snowfall region.



Overall Statistics

Table: POD and FAR of CloudSat snow detection given the NMQ as reference

	<0.2 mm/h	0.2-0.5 mm/h	0.5-1 mm/h	1-3 mm/h	>3 mm/h	All
POD (%)	75.5	76.9	84.3	86.8	69.6	79.1
FAR (%)	23.0	8.64	9.0	9.6	9.5	9.2

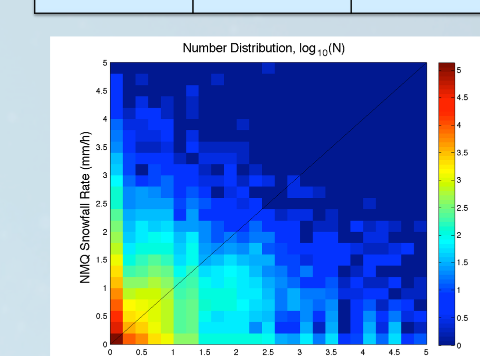


Fig. 7 Comparison of snowfall retrievals from CloudSat and NMQ (for 0-5 mm/h)

For 0.4-3 mm/h snowfall
- Bias = -0.059 mm/h
- RB (%) = -5.83
- RMSE = 0.664 mm/h
- RAE (%) = 65.4

Conclusions:

- Considering NEXRAD's worse sensitivity, the statistics of POD, FAR, and snowfall retrieval might not represent CloudSat's real potential in observing light snow.
- According to the analysis, CloudSat can not detect or retrieve the heavy snow well due to the attenuation problem.
- Detection and retrieval of moderate snowfall (e.g., 0.4-3mm/h) from CloudSat are consistent with the results from NEXRAD radar.

If you have any questions, please feel free to contact Dr. Qing Cao at OU/ARRC.
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