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 data. 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://nmp.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-SNOWPROFILE). 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 snowfall 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 to snowfall than existing weather radars
- 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.

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.

Data Matching and Statistics

1. Datasets and matching

- NMQ Precipitation Type/Phase
- NMQ Precipitation Rate
- CloudSat-D3/GEOPROF
- CloudSat-2C-SNOWPROFILE
- Time period (1/1/2009-3/2/2011)
- Found 413202 data pairs containing snow info.

2. Data pair statistics

As the left figure shows, the NEXRAD radar generally underestimates 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 type distribution, 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, CloudSat can well detect the weak snowfall echoes (high POD and low FAR) as far as NEXRAD radar can detect them. However, 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 unavailability 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.

These two case show that CloudSat well catch the temporal variation of snowfall as measured by NEXRAD radar although their snowfall retrieval might not be underestimated. 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., ~58km) while CloudSat may observe the upper atmosphere beyond 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.

Overall Statistics

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

<table>
<thead>
<tr>
<th>Snowfall Rate (mm/h)</th>
<th>POD (%)</th>
<th>FAR (%)</th>
<th>RMSE (mm/h)</th>
<th>RAE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-0.1</td>
<td>75.1</td>
<td>76.0</td>
<td>0.13</td>
<td>3.86</td>
</tr>
<tr>
<td>0.5-1</td>
<td>85.9</td>
<td>96.8</td>
<td>0.50</td>
<td>7.46</td>
</tr>
<tr>
<td>1-3</td>
<td>79.1</td>
<td>95.5</td>
<td>1.23</td>
<td>9.2</td>
</tr>
</tbody>
</table>

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.
- Depending on the analysis, CloudSat can not detect or retrieve the heavy snow fall 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 radars.