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Snowfall Detectability of NASA's CloudSat: The First Cross-Investigation of Its 2C-Snow-Profile Product and National Multi-Sensor Mosaic QPE (NMQ) Snowfall Data

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Abstract—This study investigates snowfall detectability and snowfall rate estimation with NASA's CloudSat through the first evaluation of its newly released 2C-SNOW-PROFILE products using the National Mosaic and Multisensor QPE System (NMQ) snowfall products. The primary focus is on the detection and estimation of surface snowfall. The results show that the CloudSat product has good detectability of light snow (snow water equivalent less than 1 mm/h) but degrades in moderate and heavy snow (heavier than 1 mm/h). The analysis suggests that the new 2C-SNOW-PROFILE algorithm is insufficient in correcting signal losses due to attenuation. Its underestimation is well correlated to snowfall intensity. Issues of sensitivity and data sampling with ground radars, which may affect the interpretation of the results, are also discussed. This evaluation of the new 2C-SNOW-PROFILE algorithm provides guidance for applications of the product and identifies particular error sources that can be addressed in future versions of the CloudSat snowfall algorithm.

1. INTRODUCTION

Snowfall represents a predominant portion of precipitation at mid- and high-latitude regions and considerably contributes to regional atmospheric and terrestrial water budgets. Therefore, accurate detection and estimation of snowfall is much desirable in meteorological, hydrological, and climatological applications [1, 2]. Nowadays, remote sensing technology has evolved as a practical option for monitoring snowfall, especially across regional and global scales [1, 3]. The most relevant remote-sensing instruments include ground-based weather radars and spaceborne active or passive remote sensors.

The U.S. Weather Surveillance Radar-1988 Doppler (WSR-88D) network (known as NEXRAD) has played a critical role in local weather observation, quantitative precipitation estimation (QPE), and storm monitoring and short-term forecasting. Based on high temporal/spatial resolution (5 min/1 km) measurements of NEXRAD, NOAA's National Severe Storms Laboratory (NSSL) and the University of Oklahoma have developed a Next Generation National Mosaic and Multisensor QPE System (NMQ) [4]. Since June 2006, the NMQ system has been generating high-resolution nation-wide 2D/3D QPE products that have been utilized in various applications associated with weather and precipitation. Particularly, those QPE products have been applied as the benchmark for the ground validation of precipitation measured from space [5–7]. Since July 2013 the NMQ system has been upgraded to the multi-radar/multi-sensor system (MRMS), which accommodates the recent dual-polarization upgrade of NEXRAD radars.

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Spaceborne sensors can provide global or quasi-global snow measurements, although their temporal/spatial resolutions are worse than with ground radars. Many previous efforts have been put into the use of passive microwave sensors (e.g., AMSR-E, AMSU, and TMI) for detecting snowfall or snow cover and retrieving snow depth, snow water equivalent (SWE), or snowfall rate [8–13]. Active microwave sensors also have a great potential in measuring snow. The state-of-the-art Cloud Profiling Radar (CPR) onboard NASA's CloudSat satellite is the first spaceborne cloud radar and works at W-band (94 GHz) with an along-track (or vertical) resolution of 1.4 km (or 480 m). It provides good sensitivity for measuring the vertical structure of cloud liquid and solid water distribution. While CPR is optimized for observing clouds, the sensor has proven itself capable of identifying and retrieving both light rainfall and snowfall [14, 15]. In February 2013 NASA released a novel snow profile product, 2C-SNOW-PROFILE, to the scientific community [16]. The new product provides estimates of vertical profiles of snowfall rate along with snow particle size distribution (PSD) and SWE. For these profiles, the product also yields snowfall rates at the surface.

The purpose of this study is to evaluate the snowfall detectability of CloudSat, in other words, to give the first assessment of the newly released snow profile product and to suggest specific error sources that can be improved in future versions of CloudSat snow products. The evaluation is based on the high-resolution ground radar-based NMQ snow products and focuses on the identification and estimation of snowfall near the surface. Data description, analysis, and discussion are given in Sections 2–4, respectively.

2. DATA DESCRIPTION

Scientists at the University of Wisconsin in Madison, WI are the primary developers of CloudSat's 2C-SNOW-PROFILE product. This algorithm examines variables from other well-developed CloudSat products (2B-GEOPROF, 2C-PRECIP-COLUMN, and ECMWF-AUX) so that it incorporates multi-source information from CPR, passive microwave sensors, and numerical forecast model outputs to give the optimal identification and estimation of snowfall [16]. The primary products include surface snowfall rate and the vertical profiles of snowfall rate, PSD, and snow water content. The algorithm also provides the estimation uncertainty for these variables. The formal version (P_R04) of 2C-SNOW-PROFILE algorithm was released on 10 February 2013. The CloudSat data processing center (DPC) has processed historic CloudSat data using the new algorithm and made it available for the 2C-SNOW-PROFILE product over the whole time period.

The NMQ system identifies snow reaching the surface by utilizing hourly temperature model analyses from NOAA's Rapid Update Cycle (RUC). It is noted that the since May 2012 RUC has been replaced by the Rapid Refresh (RAP), NOAA's next-generation hourly-updated assimilation/modeling system. The NMQ snow identification relies on two criteria. First, radar reflectivity measured closest to the surface must exceed 5 dBZ. Second, the surface temperature and wet bulb temperature must be lower than 2°C and 0°C, respectively. The decisions are performed for each 1-km grid cell. When a grid cell with falling snow is identified, the SWE is computed using the empirical relation $Z = 75R^{2.0}$, where Z represents the radar reflectivity ($\text{mm}^6\ \text{m}^{-3}$) and R denotes the SWE (mm h^{-1}). More details can be found in Zhang, et al. [4].

This study examines datasets of NMQ (precipitation type and rate) and CloudSat (2C-SNOW-PROFILE) from 1 January 2009 to 26 March 2011. Because the two systems have different temporal/spatial resolutions, the data must be matched prior to evaluation. The CloudSat footprint is $1.3\,\text{km} \times 1.7\,\text{km}$ and moves at the speed of 7 km/s along the track. Considering its cell size is comparable to NMQ's ($1\,\text{km} \times 1\,\text{km}$) and NMQ has a short updating time (5 minutes), data are paired using the two nearest cell centers and the two closest time stamps. That is to say, the maximum temporal/spatial mismatch of two paired cells does not exceed 2.5 minutes and 0.7 km. As a result,we have not applied any temporal/spatial interpolation or scaling during the data matching and assume the matched datasets represent similar samples. Following the data matching, we found a total of 413,202 data pairs containing snow information, i.e., the existence of falling snow has been identified by either NMQ or CloudSat. The samples sizes are all provided in Table 1. The next section gives a detailed analysis of the matched snow data.

Table 1. Number of data pairs for different categories.

		CloudSat		
		Snowfall > 0	No Snowfall	Total
NMQ	Snowfall > 0	49321	13070	62391
	No Precipitation	344613	n/a	344613
	Rainfall > 0	6198	n/a	6198
	Total	400132	13070	413202

3. ANALYSIS RESULTS

Figure 1(a) gives the occurrence distribution of snowfall detected by NMQ and CloudSat. According to the Society Automotive Engineers (SAE) Ground De-icing committee, the snowfall intensity can be classified as: light snow (< 1 mm/h), moderate snow (1–2.5 mm/h), and heavy snow (> 2.5 mm/h). In our matched datasets, light, moderate, and heavy snow data account for 85.8% (81.5%), 13.3% (17.3%), and 0.9% (1.6%) for CloudSat (NMQ), respectively. It is worth noting that NEXRAD radars have worse sensitivity than CPR in measuring light snow. As the dashed line shows, NMQ has much lower frequencies for snowfall less than 0.1 mm/h. The unnatural reduction in frequencies with lighter snowfall rates indicates NMQ's detection problems due to weak radar signals below 5 dBZ threshold discussed previously. The dashed line in Fig. 1(b) shows the scenario in which NMQ outputs no precipitation

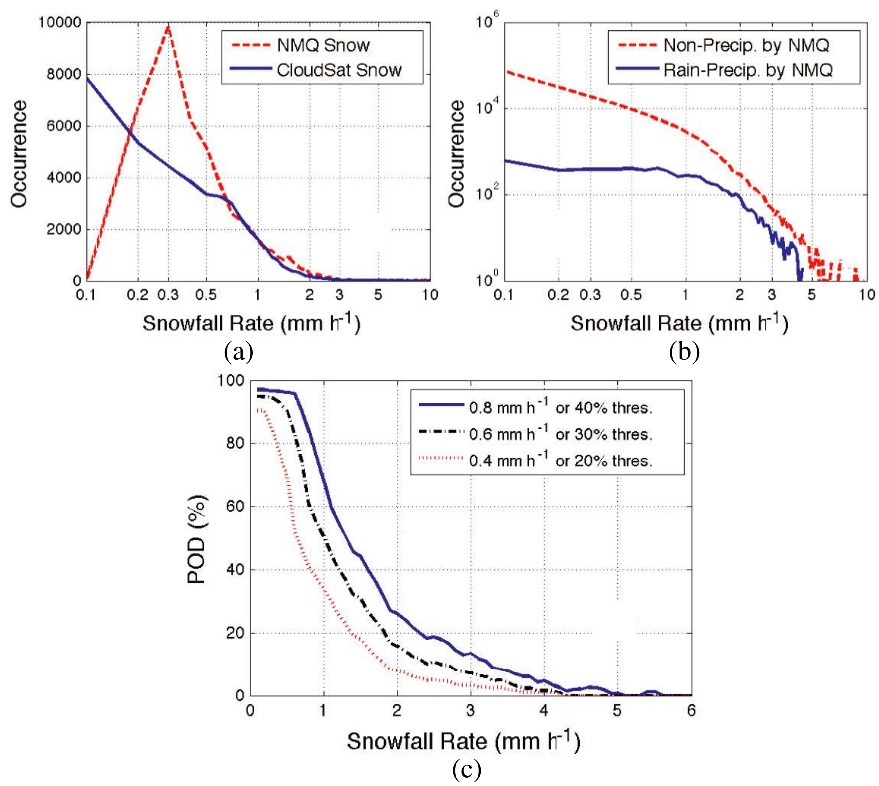
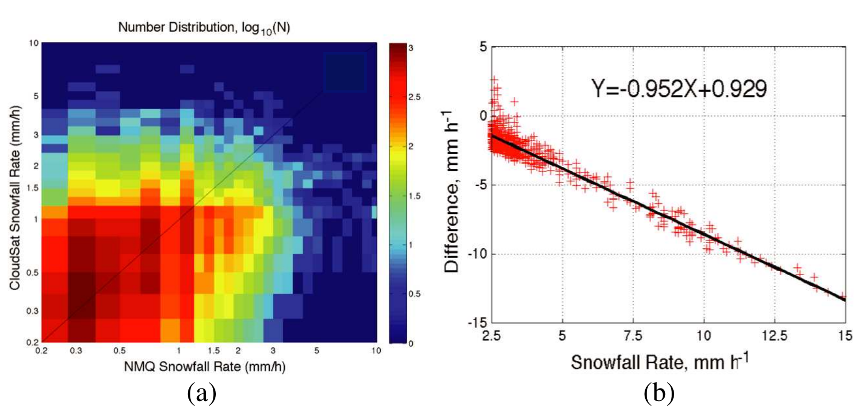


Figure 1. (a) Occurrence of snowfall identified by both NMQ and CloudSat. (b) Occurrence of snowfall identified by CloudSat but classified by NMQ as non-precipitation or rainfall. (c) The probability of detection (POD) of snowfall by CloudSat in terms of snowfall rate. CloudSat has a successful snowfall detection only when its' snowfall estimation falls into the given ranges of snowfall rate determined by NMQ. The details of threshold are given in the text of Section 3.

while CloudSat has positive snowfall rates. This analysis shows increasing instances of no-precipitation according to NMQ for lighter snowfall rates from CloudSat. The culprit for the differences is CPR's superior sensitivity compared to NEXRAD radars, a finding that was also discussed in [15]. Additional differences are due to sampling issues with ground radars. If the precipitating cloud is far from the radar or is in a shielded region, the radar beam will be overshooting the bulk of precipitation and sampling much lower reflectivity aloft in the pristine ice region. Radar overshooting is commonly caused by mountain blockages and beam broadening at far range. The solid line in Fig. 1(b) shows the snowfall measured by CloudSat but identified as rainfall by NMQ. This scenario occurs at a low frequency (only 1.5% data), and is likely a result of the differences in the surface precipitation type algorithms between NMQ and CloudSat.

Two major concerns for snowfall measurements are whether or not CloudSat can detect falling snow, and secondly, if it can accurately quantify the snowfall rate. These questions can be answered by evaluating CloudSat using NMQ as the "ground truth" while carefully considering expected errors in the NMQ product, especially at very light snowfall rates. The quantitative assessment has applied the probability of detection (POD) as a metric. Because the POD defined hereinafter relies on the NMQ benchmark, it might not be perfect to reveal the real snowfall detectability for CloudSat but could be regarded as a reasonable quantification on CloudSat's capability in measuring snowfall. The deficiency of NMQ benchmark used for the assessment will be discussed in Section 4. The POD results are shown in Fig. 1(c) with the data pairs containing the snowfall identified by NMQ. Note that this analysis will be invulnerable to the sensitivity issue with NMQ as we are only assessing the POD, not a false alarm rate. A successful detection is defined by the criteria that CloudSat successfully identifies falling snow and gives an estimate of snowfall rate close to NMQ's. The "closeness" can be determined using specific thresholds. As shown in Fig. 1(c), for example, the solid line means that the difference between CloudSat and NMQ snowfall estimates is within 40%. Considering that the differences in percentage can become quite high for light snow, a minimum threshold of 0.8 mm/h is applied as well. The three POD curves clearly show the detectability of CloudSat drops off with increasing snowfall rate. This result implies that signal attenuation has a major impact on CloudSat. It is unlikely that CloudSat yields a reasonable snowfall rate when snow is heavier than 5 mm/h. This result also implies that signal losses due to attenuation through snow have not been properly compensated in the newly-released 2C-SNOW-PROFILE algorithm. Nevertheless, snowfall detectability of CloudSat is generally good for light snow, especially for snowfall rates less than 0.4 mm/h, for which the POD is higher than 95% with less strict thresholds. Even with the strict threshold indicated by the dotted line, the POD remains more than 80%.

A quantitative comparison of NMQ and CloudSat snowfall rate estimates shows some consistency among them. The data pairs with differences greater than 2 mm/h only account for 0.8% of all the snow data. The bias and standard deviation (SD) are only 0.115 mm/h and 0.377 mm/h, respectively. The color-density scatterplot in Fig. 2(a) shows more details of the comparison. Relevant statistics are listed in Table 2. Given NMQ as the benchmark, CloudSat generally underestimates moderate-heavy snowfall



(a) (b)

Figure 2. (a) The color-density scatterplot of snowfall rates given by CloudSat and NMQ. The color scale represents the number of occurrence with the logarithmic unit. (b) The quantification of attenuation effect on the snowfall estimation by CloudSat in terms of snowfall rate.

as indicated by a progressively negative bias with increasing snowfall rates. It does not show an evident under/over-estimation of light snow but shows a large estimation error (e.g., 94.8%). Overall, the bias of CloudSat snowfall estimation is moderate and less than 27%, while the estimation uncertainty is relatively larger (65%). The uncertainty is dependent on several factors, including the data quality of NMQ, the deficiency of CloudSat, and the differences in platforms and algorithms. The next section will discuss the data quality issues that might affect the interpretation of statistical results as well as the factors that could limit the performance of CloudSat snowfall detection and estimation.

Table 2. Statistics of CloudSat snowfall estimation given NMQ snowfall rate as the benchmark. Statistics in the brackets are computed provided that the beam height is lower than 1 km above the surface.

	0–0.4 mm h^{-1}	0.4–1 mm h^{-1}	1–2.5 mm h^{-1}	2.5–10 mm h^{-1}	All
Bias (mm h^{-1})	0.049 (−0.015)	−0.086 (−0.14)	−0.70 (−0.74)	−2.45 (−2.56)	−0.19 (−0.26)
RB (%)	18.8 (−5.7)	−13.8 (−22.1)	−45.8 (−48.0)	−69.3 (−70.3)	−26.5 (−35.2)
Error (mm h^{-1})	0.25 (0.21)	0.39 (0.36)	0.84 (0.83)	2.51 (2.59)	0.46 (0.45)
RE (%)	94.8 (80.0)	62.8 (58.5)	55.0 (54.4)	70.3 (71.0)	65.0 (61.1)

4. DISCUSSIONS

The evaluation of CloudSat in this study relies on reference data from the NMQ. In regards to SWE estimation, the reliability of NMQ has not been fully justified in the literature to the best of our knowledge. Our confidence in using the NMQ (or NEXRAD) data partially comes from its superior performance with liquid precipitation measurement, which has been validated by many studies using either surface observations or cross-validation with other remote sensing sensors [7, 17, 18]. The NMQ rainfall products have also been used as the benchmark to quantify the spaceborne rainfall measurements [5–7]. The NMQ snowfall algorithm has a similar radar data processing scheme to the NMQ rainfall algorithm except it applies a different temperature criterion for snowfall identification and a different Z-S relation for snowfall rate estimation. As many previous studies have shown, surface dry/wet bulb temperatures are generally good indicators of snowfall reaching the surface [19, 20]. The NMQ snowfall Z-S relation has also been recommended by the NOAA Radar Operations Center [4]. Most importantly, NMQ has national coverage and 5 min/1 km data that provide a very large sample size of data pairs matched with CloudSat data, while other reliable sources such as surface weather stations are rather limited in their spatiotemporal coverage. Therefore, we regard NMQ as a very attractive platform to assess CloudSat's ability to detect and quantify snowfall in this study.

Despite the great utility in using NMQ as the reference, it is worthwhile to mention several factors that could affect the analysis. As shown in Fig. 1(a) and Table 1, NMQ has a notable limitation in detecting very light snow because NEXRAD radar has a lower sensitivity than CPR, and the quality control module in NMQ has further filtered out very weak signals (< 5 dBz). Therefore, the quantification for light snow may not reflect the actual potential of CloudSat. For example, the quantified error in Table 2 tends to be larger for snowfall of 0–0.4 mm/h. In reality, CloudSat performs better in measuring smaller ice particles in the precipitating cloud. It is reasonable to speculate that the detectability of CloudSat (e.g., POD, estimation bias and error) for light snow should be better than the results quantified by NMQ. Radar beam overshooting and broadening are two additional factors that could degrade NEXRAD measurements, and consequently NMQ snowfall rate estimates. Both these factors generally lead to underestimation of snowfall. To demonstrate this effect, statistics have been computed with data samples, for which the beam height is confined within 1 km above the surface, and given in the brackets in Table 2. Compared to the statistics outside brackets, the results are similar except CloudSat shows reduced errors for light snow and tends to have more negative biases, meaning NMQ snowfall rates are higher when measured closer to the surface. The benchmark data have discarded those underestimated snowfall rates so that CloudSat snowfall estimate shows more negative biases. A good example is that the snowfall of 0–0.4 mm/h changes from a positive bias to a negative bias. Generally speaking, the small differences between the statistics inside and outside brackets imply the effect of beam overshooting and broadening imparts a slight bias in the evaluation of CloudSat, but does not contribute to a significant uncertainty.

As shown throughout this study, signal attenuation at W-band frequency is a major factor that limits CloudSat's capability in snowfall detection and estimation for moderate-heavy snowfall rates. The aforementioned data analysis has shown that the current 2C-SNOW-PROFILE algorithm does not properly correct for attenuation losses. The degree of underestimation tends to be correlated with the snowfall intensity. Fig. 2(b) shows the estimation difference between CloudSat and NMQ for heavy snow (i.e., > 2.5 mm/h). The data points ("cross" mark) show a linear relation represented by the solid line as $Y = -0.952X + 0.929$. This relation indicates that attenuation may cause a 55.3% underestimate for snowfall of 2.5 mm/h. The underestimation increases with snowfall intensity and can reach 90% when the snowfall rate exceeds 20 mm/h. The trend line quantifying the attenuation effect in moderate snow (i.e., 1–2.5 mm/h) has a similar trend (not shown) but a slighter slope. The relation between attenuation and snowfall rate is quantified as $Y = -0.815X + 0.540$. The attenuation effect is difficult to quantify for light snow (< 1 mm/h) given the relatively large uncertainty of light snow measurements by NEXRAD radars. However, it is generally accepted that the attenuation effect is small for light snow and can be reasonably ignored.

5. CONCLUSIONS

The current study investigates snowfall detectability and snowfall rate estimation of CloudSat through the first evaluation of the newly released 2C-SNOW-PROFILE product. The evaluation is based on ground radar-based NMQ snowfall products and focuses on the identification and estimation of surface snowfall. The uncertainty of NMQ snowfall data has yet to be quantified through comparison with in-situ sensors, and there is less sensitivity at S-band frequency with very light snowfall rates. Nevertheless, the comparison benefits from very large sample sizes with data that are matched quite closely in space, time, and pixel resolution. The NMQ-based evaluation indicates that CloudSat has good detectability in light snow but suffers from the attenuation effect for moderate-heavy snow. The POD of falling snow is generally high (e.g., $\sim 90\%$) for light snow and decreases with increasing snowfall intensity, yielding very poor detectability for snowfall rates heavier than 5 mm/h. CloudSat quantitative snowfall estimates are generally consistent with NMQ data, but the attenuation effect is evident again for moderate-heavy snow. A major outcome of this study is the apparent inability of the 2C-SNOW-PROFILE algorithm to properly correct for signal losses due to attenuation. The analysis indicates that bias due to the attenuation losses increases proportionally to the snowfall intensity.

As the new 2C-SNOW-PROFILE algorithm undergoes continuing evaluations and subsequent algorithm improvements, the current evaluation gives some initial insights into the performance to date and has revealed some errors that need to be addressed. Future work will investigate the hypothesized error sources in more detail through integration of additional ancillary data sources.

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