Evaluation of CloudSat rainfall retrievals over land using operationalWSR-88D radar data

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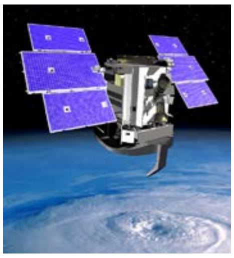
(Dated: 1 July 2014)



CloudSat

1 Introduction

CloudSat rain rate estimation methods have to utilize 94 GHz cloud profiling radar (CPR) signal attenuation effects as useful information for liquid precipitation retrievals (e.g., Matrosov et al. 2008; Haynes et al. 2009; Lebsock and L'Ecuyer 2011). These effects are used with *CloudSat* data in different ways. Most existing methods use the path-integrated attenuation (PIA) constraint, which is determined assuming that radar returns from the surface in clear air are known with a reasonable accuracy. The application of the PIA-based retrieval approaches, such as those used to derive the existing *CloudSat* rainfall 2C-PRECIP-COLUMN (Haynes et al. 2009) and 2C-RAIN-PROFILE (Lebsock and L'Ecuyer 2011) products, are currently limited to CPR measurements over water, when would-be surface returns in the absence of hydrometeors in a vertical atmospheric column are approximated based on a priori information about surface wind speed and temperature. The use of the PIA constraint is not generally available for heavier rainfall when the surface returns are not detected due to a combination of very strong attenuation and multiple scattering effects (e.g., Battaglia et al. 2008).

A reflectivity gradient method to retrieve rain rates from *CloudSat* data (e.g., Matrosov et al. 2007) estimates the W-band attenuation coefficient in rain from the vertical gradients of observed CPR reflectivities and then relates this coefficient to *R*. This method does not use the PIA information from surface returns and, thus, is applicable to observations above any surfaces. The main assumption of this method is that after accounting for gaseous attenuation the vertical gradients of observed reflectivities are primarily caused by liquid hydrometer attenuation and, for heavier rainfall, by multiple scattering enhancement. Changes in a vertical profile of non-attenuated reflectivities contribute to the uncertainty of the attenuation coefficient (and thus rain rate) estimates. Given this assumption, the reflectivity gradient method is best suited for stratiform precipitation where vertical variations in non-attenuated reflectivity profiles are relatively small even at centimeter wavelengths, which are typically used in ground-based precipitation sensing radars. At W-band the vertical variability of non-attenuated reflectivity in stratiform rain is further suppressed compared to longer wavelengths because of strong non-Rayleigh scattering effects.

This study provides an evaluation of the *CloudSat* gradient method rain rate retrievals in stratiform rainfall over land using ground-based scanning S-band (~3 GHz) Weather Surveillance Radar-1988 Doppler (WSR-88D) measurements. The WSR-88D data are routinely used over the U.S. for quantitative precipitation estimation (QPE) purposes. While uncertainty of WSR-88D QPE retrievals could be as high as 30-40% as compared to rainfall accumulations directly observed by rain gauges, which are often considered as the "ground truth" (e.g., Krajewski et al.2010), the scanning precipitation radar based QPE retrievals remain the main remote sensing tool for obtaining precipitation information in many practical applications.

2. Data sets

This study focuses on rain rate comparisons as retrieved from *CloudSat* and WSR-88D measurements with the best possible collocation in space and time. Although WSR-88D-based QPE retrievals obviously are not exactly the "ground truth", such comparisons have a value because relatively novel *CloudSat* rain rate retrievals over land are compared to the results from the ground-based meteorological radar QPE approach, which has been in practical use for many years and is relatively well established. It should be realized, however, that instantaneous rain rates generally exhibit higher spatial and temporal variability compared to rainfall accumulations during fixed time intervals (e.g., hourly accumulations).

Intercomparisons of WSR-88D and *CloudSat* CPR retrievals are most practical for precipitation events observed when the satellite crosses over the ground-based radar sites (or over locations in the vicinity of these sites), where ground-based and spaceborne retrievals could be better collocated. *CloudSat* ground tracks pass within few kilometers of a number of the WSR-88D sites. This study considers the precipitation events observed in the vicinity of two weather service radars, namely the KGWX Greenwood Springs, MS radar (N 33.8969°, W 88.3292°) and the KSHV Shreveport, LA radar (N 32.4508°, W 93.8414°). The site altitudes for these radars above the mean sea level (MSL) are approximately 140 m and 80 m for KGWX and KSHV, respectively.

CloudSat passage over a particular ground-based radar site during a precipitation occurrence in the vicinity of this radar site is a relatively rare event because the orbit revisit time interval is 16 days. Of the main interest to this study were precipitation events which consisted mostly of stratiform rain regions covering relatively large areas (at least several dozens of kilometers). This allows for better collocation of satellite and ground-based retrievals and results in more data points for comparisons. Stratiform rainfall typically produces radar bright band (BB) located just below the freezing level. Unlike the BB in longer-wavelength radar observations, the BB in CPR measurements is caused, in part, by strong signal attenuation in liquid hydrometeors (Matrosov 2008).

Examining the available *CloudSat* overpasses, which occurred over the KGWX site during 2006 - 2012, revealed six predominantly stratiform rainfall events, for which horizontal extents along the *CloudSat* ground track exceeded about 50 km and freezing level heights were greater than a threshold of 2 km required for calculating reflectivity gradients. These events, which are typically associated with the passage of frontal atmospheric systems, and are shown in Fig. 1. The *CloudSat* orbit crossings over the vicinity of the KGWX ground-based radar site occur on the ascending satellite node at approximately 1915 UTC. It corresponds to 1415 CDT at the site location. The same number of precipitation events with the same characteristics (i.e., mostly stratiform rainfall with a detectable bright-band covering a horizontal range over approximately 50 km in the ground-based radar coverage area) was observed also when the *CloudSat* crossed over the vicinity of the KSHV radar site during 2006-2012. These events are also shown in Fig.1. The KSHV site crossings occur on the descending satellite node. The crossing time is approximately 0820 UTC, which corresponds to night time at the KSHV location.

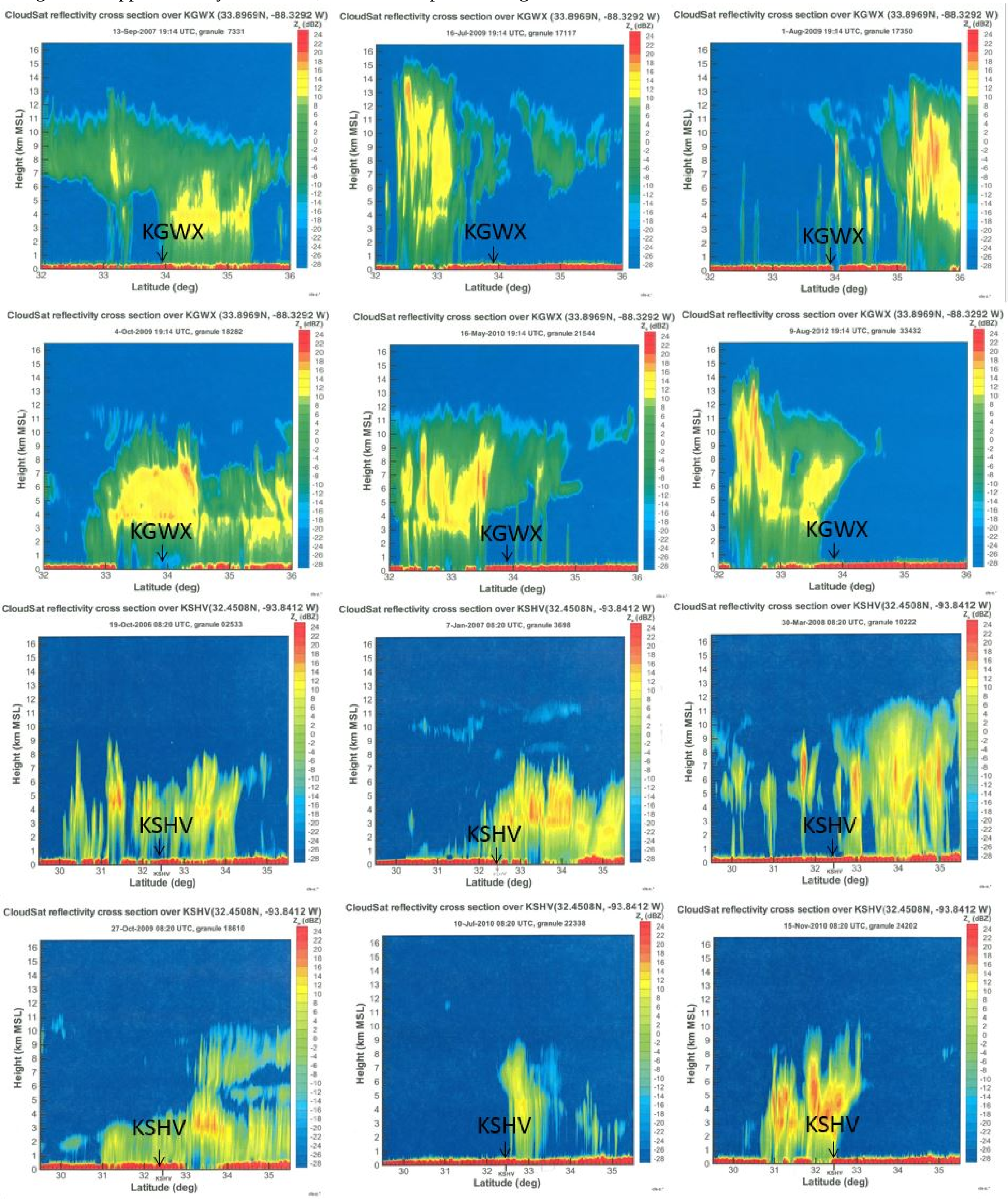


Figure 1: Comparisons events over the KGWX radar site (upper six frames) and over the KSH radar site (lower six frames).

3. Collocating CloudSat and ground-based radar sampling volumes in space and time

Volume scans of WSR-88D measurements were used to reconstruct cross sections of ground-based radar reflectivities which closely match the *CloudSat* CPR reflectivity cross sections during passages over WSR-88D sites. An example of such collocations for one experimental events is shown in Fig. 2. In addition to the spatial interpolation and averaging of the WSR-88D reflectivity data, the linear time interpolation of the ground-based radar measurements was performed using two consecutive volume scans which bracket the CPR reflectivity cross section time. All the interpolation/averaging procedures for a given tilt data mentioned above were performed for the WSR-88D S-band reflectivity measurements in the $mm^6 m^{-3}$ units.

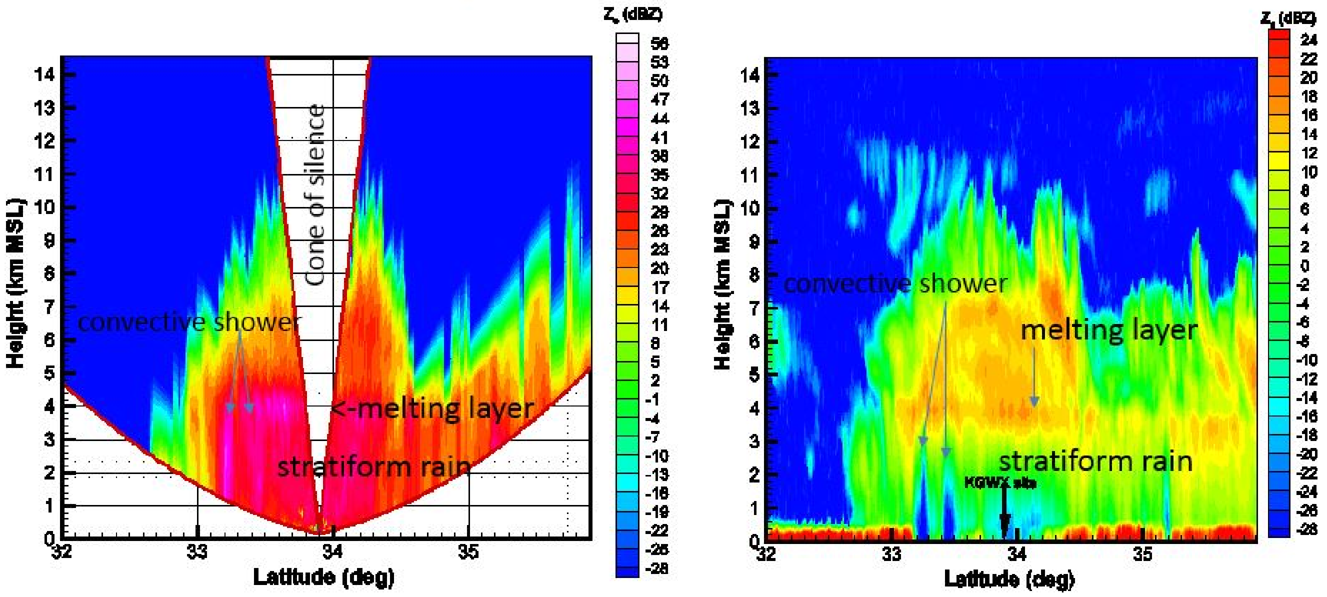


Figure 2: Collocated cross sections of WSR-88D (left) and CPR (right) reflectivities of the 4 October 2009 precipitation event during the CloudSat passage over the KGWX radar site.

It can be seen from Fig. 2 that in spite of the coarser resolution of the WSR-88D reflectivity cross section, it reproduces general vertical features of the precipitating system seen in the CPR data including higher cloud tops between latitudes of about 33.2^o and 34.5^o, and some isolated reflectivity spikes (e.g., near 35.5^o). Except the vicinity of the radar site (i.e., approximately between 33.4^o and 34.3^o), the radar BB are not very well pronounced in the KGWX data. This can be explained by the radar beam broadening effects, which degrade the actual WSR-88D resolution with increasing range. The closely collocated in space and time *CloudSat* CPR and KGWX WSR-88D measurements, such as those shown in Fig. 2, allow for detailed intercomparisons of the spaceborne and ground-based rain rate retrievals with proper matching satellite and ground based radar rain rate estimates.

Although the WSR-88D network was polarimetrically upgraded during 2012-2013 and new dual-polarization radar QPE approaches are being developed, the WSR-88D data collocated with *CloudSat* measurements available to this study include only the WSR-88D reflectivity and Doppler velocity measurements. Thus the conventional WSR-88D rain rate retrievals based on S-band reflectivity (Z_e) are considered here for intercomarisons. Such retrievals are used in the National Mosaic and QPE system (NMQ) (e.g., Zhang et al. 2011). The standard NEXRAD Z_e - R relation for stratiform rainfall, which is given by (e.g., Zhang et al. 2011):

$$Z_e\ (mm^6\ m^{-3}) = 200\ R^{1.6}\ (mm\ h^{-1}), \quad (1)$$

was primarily utilized with ground-based WSR-88D measurements in this study. In order to estimate the intercomparison results variability, another commonly used WSR-88D relation:

$$Z_e\ (mm^6\ m^{-3}) = 300\ R^{1.4}\ (mm\ h^{-1}), \quad (2)$$

was also utilized in ground-based radar QPE retrievals.

3. Statistical intercomparisons

The intercomparison of WSR-88D and *CloudSat* rain rate retrievals from all precipitation events (see Fig. 1) of collocated WSR-88D (including the KGWX and KSHV radars) and CPR rain rate retrievals were performed. Fig. 3a shows the intercomparison results. The mean rain rates in vertical columns, which correspond the CPR measurement profiles are shown. The retrievals at heights where both WSR-88D and CPR measurements exist within a given column were used to calculate these mean rain rates. The presented data correspond to the rainfall exhibiting the bright band as detected by the *CloudSat* measurements. The Z_e-R relation (1) was used with for WSR-88D retrievals. Although most such rainfall can be considered as stratiform, some local areas of convective rain with elevated bright band features can be present as seen in Fig.1.

To assess intercomparisons of rain rate retrievals in a quantitative sense, the correlation coefficient, r, between CloudSat and WSR-88D estimates (i.e., R_C and R_N respectively), as well as different statistical parameters characterizing the retrieval intercomparisons were calculated. These statistical parameters include the normalized relative mean bias (RMB):

$$RMB = \langle (R_C - R_N) \rangle \cdot \langle R_N \rangle^{-1} \cdot 100\ \%, \qquad (3)$$

and the normalized mean absolute difference (NMAD):

$$NMAD = \langle |R_C - R_N| \rangle \cdot \langle R_N \rangle^{-1} \cdot 100\ \%, \qquad (4)$$

where angle brackets denote averaging with respect to the whole data set.

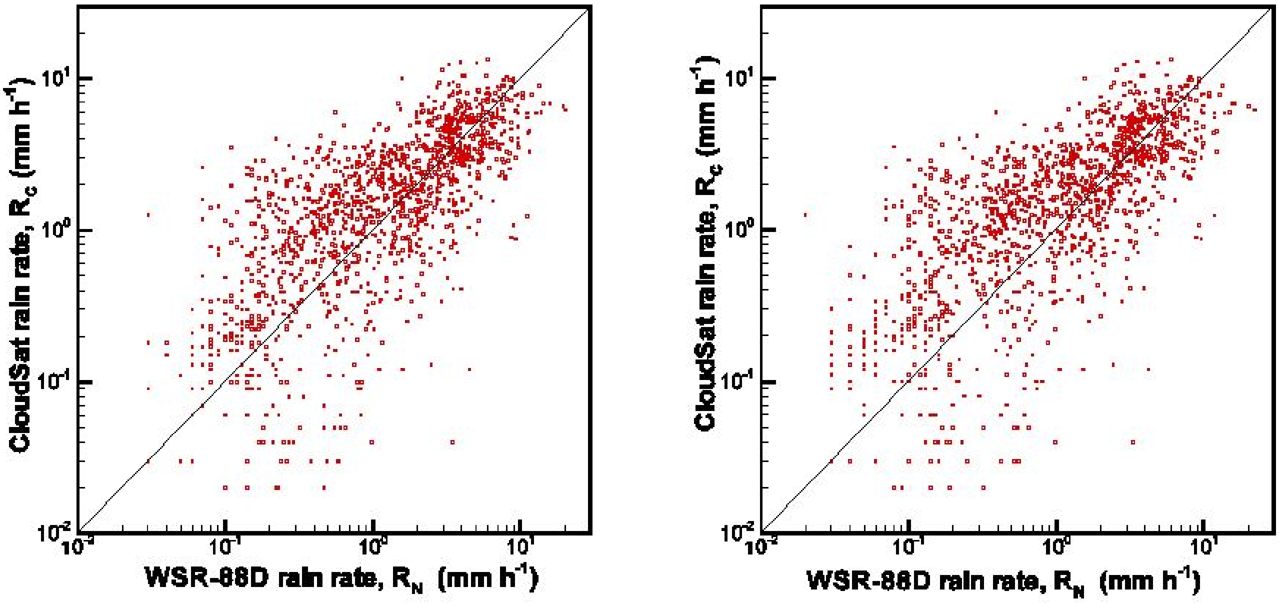


Figure 3:Scatter plots of rain rates retrieved from collocated CloudSat and WSR-88D measurements. The default WSR-88D relations (1) and (2) used in the left and right frames, respectively.

It can be seen from the intercomparisons presented in Fig. 3, that there is a relatively good agreement between spaceborne and ground-based radar retrievals of rain rate. The corresponding correlation coefficients are around 0.6-0.7 and the RMB, and NMAD values are about 10-15%, and 60%, respectively. Overall the data scatter which is characterized by the NMAD values, is within the joint uncertainties of both types of retrievals. This scatter is higher for lower rain rates (< 1-2 mm/h), which can be explained, in part, by higher *CloudSat* retrieval uncertainties for lighter rainfall.

4. Conclusions

Intercomparisons of rain rates retrieved using the *CloudSat* reflectivity gradient method during the satellite overpasses above weather service ground-based radars showed a good agreement with closely collocated estimates obtained from these radars using standard WSR-88D approaches. The intercomparisons were conducted for mostly stratiform rain exhibiting bright band, though some areas of moderate convection were also present. The observed good agreement indicates a general robustness of the reflectivity gradient method, which can be used for rain retrievals from *CloudSat* radar measurements over the land surfaces.

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