P3.14

ESTIMATIONS OF PRECIPIATION RATES FROM CLOUDSAT MEASUREMENTS

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1. INTRODUCTION

The world's first satellite-borne W-band (94 GHz) nadir-pointing cloud radar (CloudSat) was launched in April 2006. Since June 2006, CloudSat has been successfully collecting data. The ground-based W-band radars have been shown to be a valuable tool for studies of non-precipitating clouds. Hence, the main objective of the CloudSat radar is to acquire global information on clouds. This radar, however, resolves many precipitating cloud systems, so it was suggested (even before the launch) that it can be used also for retrievals of drizzle and light rainfall parameters (e.g., Stephens et al. 2002).

The recent experience with CloudSat data shows that the space-borne W-band measurements can also be used for estimations of heavier rainfall and snowfall parameters. This makes CloudSat an important tool in the research of the Earth water cycle since the satellite's sun-synchronous polar orbit allows an almost global coverage.

2. CLOUDSAT RAINFALL RETRIEVALS

The traditional non-polarimetric radar approaches for rainfall retrievals are usually based on relating the equivalent radar reflectivity factor, Z_e, to rain rate, R. Attenuation of radar signals in rain has been always considered as a factor that impedes rain retrievals. Special techniques have been developed to account for attenuation in rain at the radar frequencies where this attenuation is significant. As a result of application of such techniques, non-attenuated values of reflectivity are estimated and then they are related to rain rates. These approaches typically perform best when attenuation corrections are relatively small compared the values of non-attenuated reflectivities, and these reflectivities exhibit a strong sensitivity to rain rates.

The W-band radar frequencies, however, attenuation of radar signals in rain is very strong. At the same time, due, to strong resonance scattering, radar reflectivity and rainfall rate are not strongly related. These two factors make it possible to apply non-traditional attenuation-based radar approaches for rain rate retrievals.

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Figure 1a shows scatter-plots of W-band non-attenuated reflectivities, Z_{en}, and rain rates as calculated for experimental rain drop size distributions (DSDs) observed during two different field experiments.

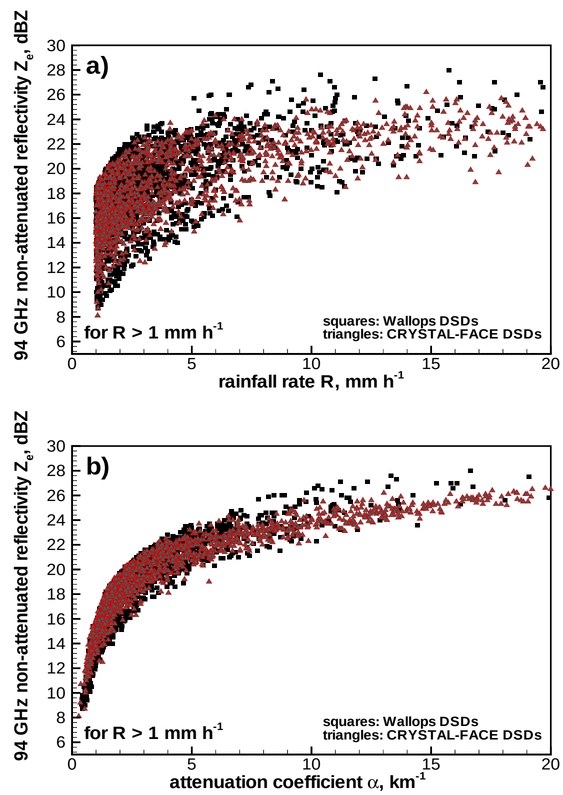

FIG.1. Scatter plots of Z_{en} and R (a) and α and R (b) as calculated from experimental DSDs.

It can be seen that there is almost no (or very little) relation between Z_{en} and R , for $R > 4$ mmh^{-1}. The variability due to DSD details dominates for these rain rates. Relation between the attenuation coefficient in rain, α, and R at W-band [shown in Fig. 1(b)] is also very weak for such rain rates, though there is less sensitivity to DSD details.

Unlike for Z_{en} and R, a relation between α and R at W-band is very strong and close to be linear. The scatter plot illustrating this relation is shown in Fig. 2. Variations caused by DSD details are, however, relatively significant.

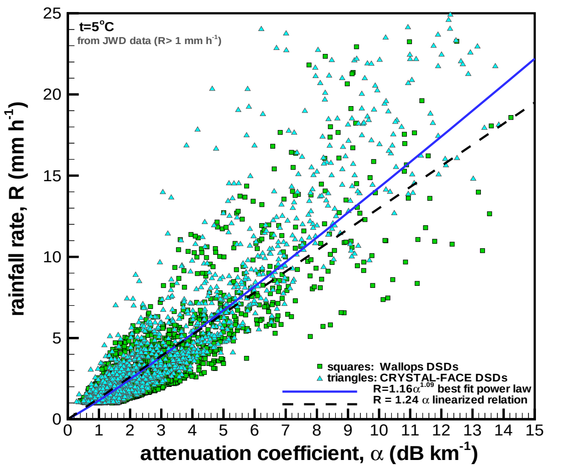

FIG.2. A scatter plot between the attenuation coefficient in rain at W-band and rain rate.

The results shown above indicate that attenuation in rain is dominant factor that causes changes of measured radar reflectivity with range. Thus the attenuation-based approach suggested earlier for rain rate retrievals using the ground-based K_a-band radars (Matrosov 2005; Matrosov et al. 2006) can be applied for W-band radar measurements. The advantage of W-band over K_a-band, as it comes for applications of the attenuation-based approaches, is in a stronger attenuation in rain and in a very subdued sensitivity of Z_{en} to R . The main K_a-band advantage is a practically linear relation between α and R, and a very low influence of DSD variations on this relation.

Under the attenuation-based approach, the attenuation coefficient is estimated as a half of the range (i.e., height) derivative of measured reflectivity, and then the estimate of α is related to the rainfall rate using the mean relation between α and R. The variability to DSD details and changes in non-attenuated reflectivity contributes to the uncertainty of rain rate estimates. This uncertainty can be approximately estimated as about 40% for $R > 4 - 5$ mm h^{-1} (Matrosov 2007a). Additional uncertainties are possible due to effects of multiple scattering (Battaglia et al. 2005).

Figure 3 show an example of attenuation-based CloudSat retrievals of rain rate. The reflectivity enhancement due to ice hydrometeor melting can be seen in Fig. 3a just above 4 km MSL. Attenuation causes a rapid decrease in measured reflectivities with range in the rain layer, but surface returns are still observed. A time-height cross section of rain rate profile retrievals is depicted in Fig. 3b. The effective spatial resolution of the retrievals (i.e., the height interval at which range derivative is estimated) is 1.2 km, though estimates are obtained at each CloudSat resolution range except the vicinity of the surface and the melting layer. Corrections for the gaseous attenuation are introduced based on the standard atmosphere stratification and an assumption of 100% humidity in the rain layer. As an example, an individual profile of retrieved rain rate is also shown in Fig. 3b.

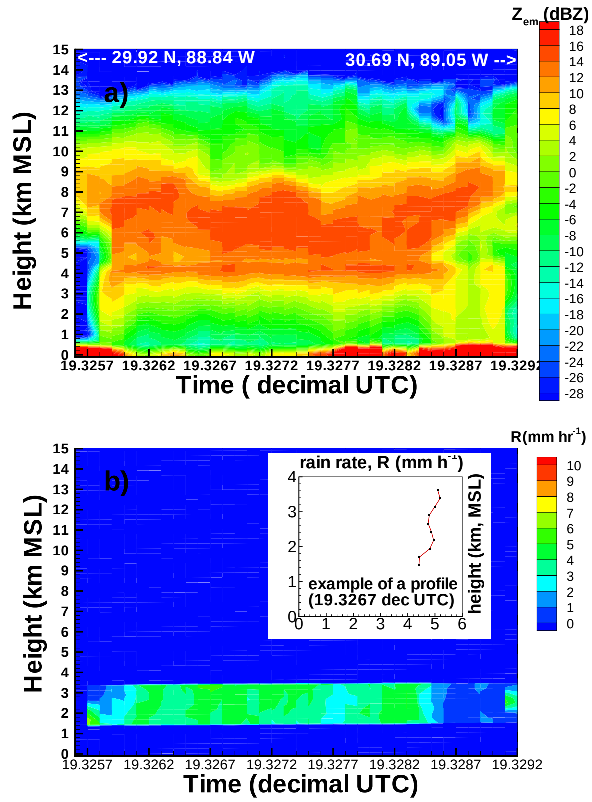

FIG.3. Time-height cross sections of the CloudSat measurements of the precipitating system (a) and the corresponding rain rate retrievals (b). 31 July 2006.

CloudSat attenuation-based retrievals have been compared with coincident estimates of rainfall from the ground-based Weather Surveillance Radar - 1998 Doppler (WSR-88D). It should be noted that while the WSR-88D uncertainties could be large, these weather service radars provide one of only few options of validating CloudSat rainfall retrievals. The comparisons indicated a general agreement of space-borne and ground-based rain rate estimates, though differences, at times, were as large as a factor of two. Occasional large differences, however, should not be very surprising because given the uncertainties of both types of the retrievals.

3. CLOUDSAT SNOWFALL RETRIEVALS

Attenuation of W-band radar signals in snowfall is relatively small compared to rainfall unless snow is moist. As a result, the attenuation-based approaches are not applicable for snowfall rate estimates, and a viable retrieval method should use absolute reflectivity measurements. A specifically tuned for W-band relation between Z_{en} and liquid equivalent snowfall rate, S, was suggested by Matrosov (2007b) [$Z_{en} = 10\ S^{0.8}$, where Z_{en} is in mm^6 m^{-3}, and S in mm h^{-1}]. This relation accounts for mean snowflake shapes and is based on experimental measurements of snowflake size distributions.

An example of the CloudSat snowfall measurements is presented in Fig. 4, where a time-height cross section of W-band radar reflectivities (a) and the corresponding estimates of snowfall rate (b) are depicted as the satellite crossed over an area of heavy snowfall in Northern Colorado and Southern Wyoming on 21 December 2006. The layer of increased reflectivity between about 1 and 2 km MSL represent range gates contaminated by the ground returns. This case was relatively cold and snowflakes according to the ground observations were mostly "dry" with a very limited degree of riming.

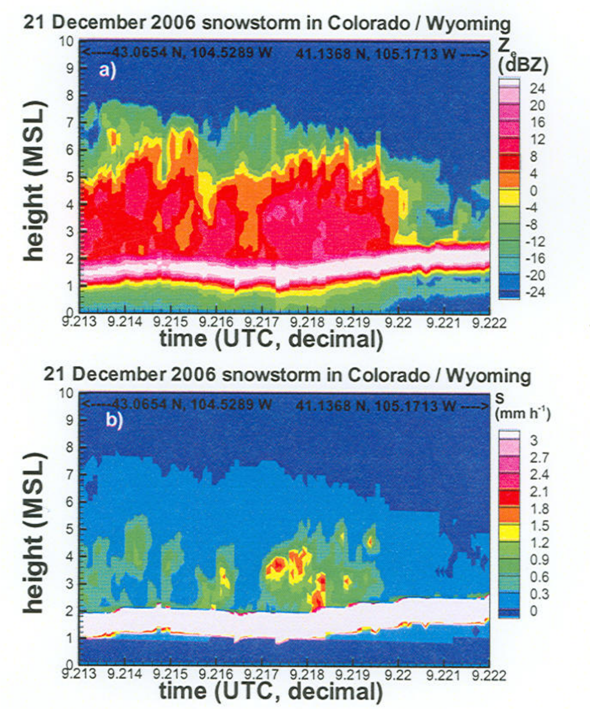

FIG.4. Time-height cross sections of measured CloudSat reflectivity (a) and estimated snowfall rate (b) for a snowstorm observed in Southern Wyoming on 21 December 2006.

Figure 5 shows the Cheyenne WY WSR-88D radar estimates of snowfall rate along the CloudSat ground track. An S-band (i.e., the WSR-88D radar frequency) snowfall rate - reflectivity relations specifically tuned for this geographical area was used for the Cheyenne radar data. Also shown in Fig. 5 are space-borne snowfall rate estimates. In case of CloudSat, measured radar reflectivities were corrected for gaseous and snowfall attenuations according to Matrosov (2007b).

To provide some information on vertical variability of instantaneous snowfall, CloudSat retrievals, are shown at altitudes 2.6 and 3.6 MSL. It can be seen that both CloudSat and the Cheyenne WSR-88D radar observe similar snowfall patterns. Overall the space-borne ground-based retrieval comparisons could be considered quite satisfactory. Note that, as for rainfall comparisons, these snowfall comparisons present a consistence check, and they cannot be regarded as a strict validation effort.

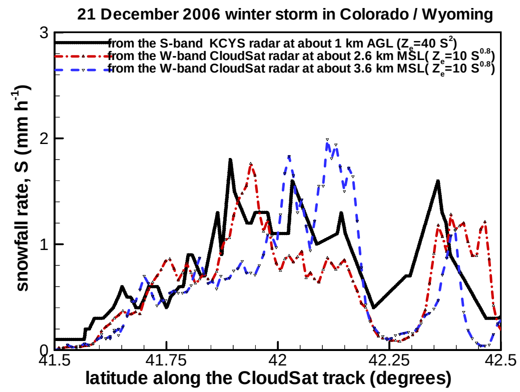

FIG.5. Comparisons of the CloudSat and Cheyenne WY WSR-88D radar estimates of snowfall rates

5. CONCLUSIONS

Space-borne CloudSat measurements can be successfully used for estimating precipitation rates. In case of rainfall, an attenuation-based approach shows a potential for global rain rate estimates. Under this approach, changes of measured radar reflectivity with height caused by the attenuation are the useful signals while the variability of non-attenuated reflectivity contributes to the retrieval uncertainty. This approach is immune to the radar absolute calibration, does not require a surface reference and is applicable to a wide range of rain rates.

CloudSat snowfall estimates need to be based on absolute reflectivity measurements, thus they require a good absolute calibration of the radar. A Z_{en} – S relation specifically tuned for W-band was used for CloudSat retrievals of snowfall rate. Comparisons of CloudSat-based rain and snowfall rates were shown to be consistent with estimates obtained with weather service precipitation radars

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