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AN ASSESSMENT OF CLOUDSAT PRODUCTS USING THE ENVIRONMENT CANADA OBSERVING NETWORK

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1. INTRODUCTION

In April 2006, the NASA/CSA CloudSat mission satellite with a 94GHz Cloud Profiling Radar (CPR) aboard was launched as part of the "A-train" constellation of satellites. The sun synchronous polar orbit provides an unprecedented opportunity for viewing cloud and precipitation features with a cloud radar throughout all of Canada including the far north. This paper deals with the validation of CloudSat-derived macroscopic cloud and precipitation features. It makes use of measurements using the Environment Canada weather radar network to provide independent ground truth. The information will also be valuable as part of the development of experimental precipitation rate products from CloudSat. This effort is part of the larger Canadian CloudSat / CALIPSO Validation Project (C3VP) as described in Hudak et al. (2006a, 2007).

2. DATA SOURCES

The CloudSat data products that are considered are the 2B-GEOPROF and 2B-CLDCLASS which include fields for CPR reflectivity, cloud detection mask, cloud type and precipitation occurrence and type (Stephens et al., 2002).

The CloudSat Data Processing Center (DPC) provides an on-line ordering system (web GUI) to select and depot in Hierarchical Data Format for Earth Observing System (HDF-EOS) data files for FTP download. All orbits that crossed Canada from the beginning of September, 2006 to the end of March, 2007 were assembled and used in this study.

A customized cross-language (IDL and C code) satellite tracking package based on the SGP4/SDP4 orbital model by Dr.TS Kelso, 1992 (Pascal code package ported to C by Neoklis Kyriazis, 2001) was used to select the required orbits. This code is run by C3VP using the latest Two Line Element from the DPC to produce a 16-day forecast of the CloudSat satellite track (see http://c3vp.org/data/ORBITS/prediction/CloudSat_prediction.html. A sample track is shown in Fig. 1.

The EC ground observing network spans Canada (Hudak et al., 2006) and consists of a) 31 C-band National Radar Program (NRP) Doppler radars (Joe and Lapczak, 2002); b) more than 200 weather observing stations; and c) 15 enhanced Precipitation Occurrence Sensors Systems (POSS) (Sheppard and Joe, 2000) providing additional precipitation information.

One of the radars in the EC network, the King City radar, was recently upgraded to dual polarization capabilities (Hudak et al., 2006b). There were special RHI scans timed to the passage of CloudSat directly overhead (as in Fig. 1) in addition to the normal volume scanning.

The satellite tracking software permitted the determination of the relevant intersected volume scans from the Canadian radar network for each of the 16 days of the CloudSat orbit cycle. It is the basis for tabulating which CloudSat granule numbers and EC network files should be extracted.

The NRP radar scan data are acquired twice a day (for the ascending and descending series of Canadian overpasses) by means of an automated script that retrieves the relevant files from a centralized NRP server at the Canadian Meteorological Centre (CMC) in Montreal.

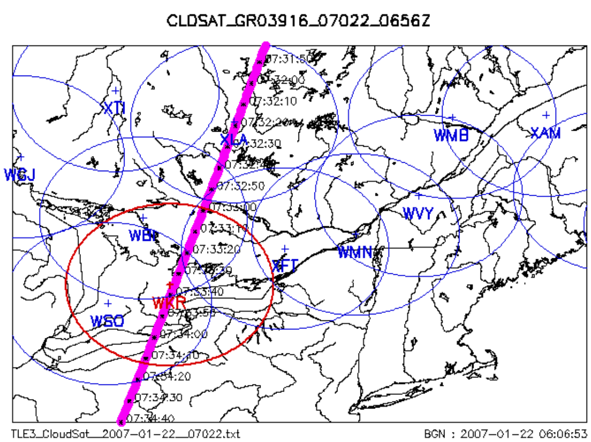

Figure 1: 2007-Jan-22 CloudSat track (magenta) over Southern Ontario & Quebec and NRP radars (blue). The King City (WKR) radar coverage area is shown in red

3. METHODOLOGY

The non-scanning nadir viewing of the CloudSat CPR presented a number of challenges in matching the NRP radar data. In comparison, in the ground validation of TRMM, the scanning nature of the TRMM radar permitted validation from a number of ground sites as well as horizontal PPI depictions of ground radar data (Wolfe et al., 2005). Furthermore, for CloudSat adjacent

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orbits are spaced approximately 120 km apart over southern Canada, the width of the radar footprint is 1.4 km. So in effect, it would be rare for the CloudSat beam to direct intersect a surface weather station. Arbitrary volume cross-sections (AVCS) derived from the volume scan data from the NRP radars matched to the CloudSat track was the only viable means of acquiring a matched data set.

For the period of 2006-Sep-02 to 2007-Apr-01, 3824 ground radar volumes were matched with data from CloudSat granules.

The NRP 2conventional volume (CONVOL) scan consist of 24 top-down PPI levels with a 250 km range and a range resolution of 0.25 km taken every 10 min. Ground clutter removal is not applied to the CONVOL data.

The CloudSat CPR data matching algorithm was written in IDL and makes extensive use of creating IDL SAV files. The steps involved in the creation of an AVCS from a CONVOL were as follows.

a) CloudSat data was natively referenced by range from the satellite. Each profile's height read back was used to build an above sea level ground-based height-time indicator (HTI) version of the CloudSat swath.

b) Created a look-up table (LUT) for each radar site. A ground range and height grid of references to the CONVOL's closest slant range bin and PPI level pair was calculated (sample LUT shown in Fig. 2). The grid corresponded to heights below 20km with a height resolution of 240m to match CloudSat's data resolution. The LUT grid provided the information to build vertical profiles given a ground range value. In this approach, no interpolation was performed – the closest actual measurement was used.

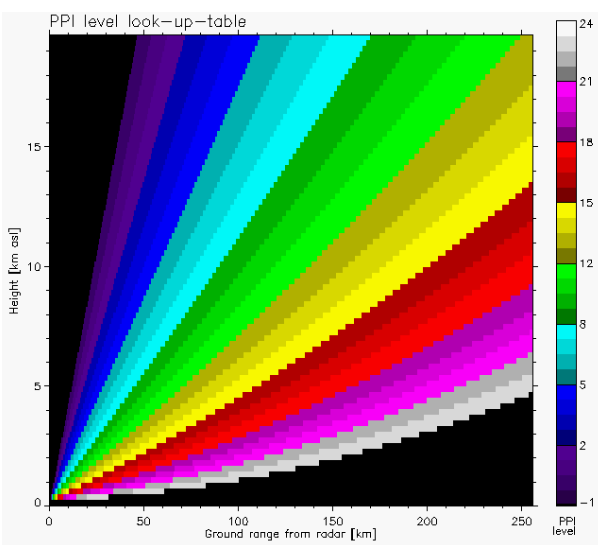

Figure 2: The look up table of the 24 PPI levels for the XME radar volume scan on a ground range versus height grid.

b) For each vertical profile within a CloudSat swath its ground range and azimuth coordinate with respect to the radar origin was determined. In this approach, the AVCS construction could handle non-linear paths.

c) From the CloudSat swath's ground range and azimuth series corresponding CONVOL vertical profiles were extracted.

A couple of remarks, the CloudSat swath may intersect multiple radar sites. Also the further it intersects from the radar origin, then the bottom of the AVCS rises. The bottom of the AVCS bowl is indicated in red in the matched products (Fig. 3).

4. DISCUSSION

Fig. 3 is a comparison of the reflectivities for the 2006-09-21 CPR granule #2124 matched to the XME (Marble Mountain, Newfoundland) NRP ground radar. It is evident here on the C-band ground radar product, sensitivity to clouds decreases with range. At point A on Fig. 3, the XME radar cannot detect the cloud layer at 8 km height. Closer to the XME radar where the sensitivity is higher, the reflectivities between CPR and AVCS from XME match at cloud top where the CPR would not be experiencing significant attenuation. The consistency of the rough geometric cloud profiles lends confidence to the matching methodology. For example, both W- and C-band show the gaps between cloud cells at point B, and 3 cloud layers at closer ground radar range at point C.

Fig. 4 is a composite overlay of CloudSat and AVCS-based echo masks. In the lowest levels, there are a couple of notable discrepancies. Firstly, the CPR is seen to lose data in lowest levels compared to the AVCS due to the masking of the data by the surface return (point A). This could result in underestimate of crucial cloud properties in shallow systems.

Secondly, strong echoes cause significant attenuation of the CPR signal such as at point B in Fig. 4. Here the CPR signal is strongly attenuated below 3 km. The difference between CPR and the AVCS is some 40 dBZ (Fig 3. location D).

These are two ways in which low altitude CPR reflectivity values could introduce difficulties in making a qualitative statement about what may be happening at the surface.

It is noteworthy however that the 2B-GEOPROF algorithm had recognized that attenuation was occurring at point B and preserved a valid echo mask designation (magenta indicates that both CPR and NRP detected echoes).

The next version of CloudSat products will be implementing a ground clutter removal algorithm which hopes to significantly improve echo detection within two additional near-surface range bins.

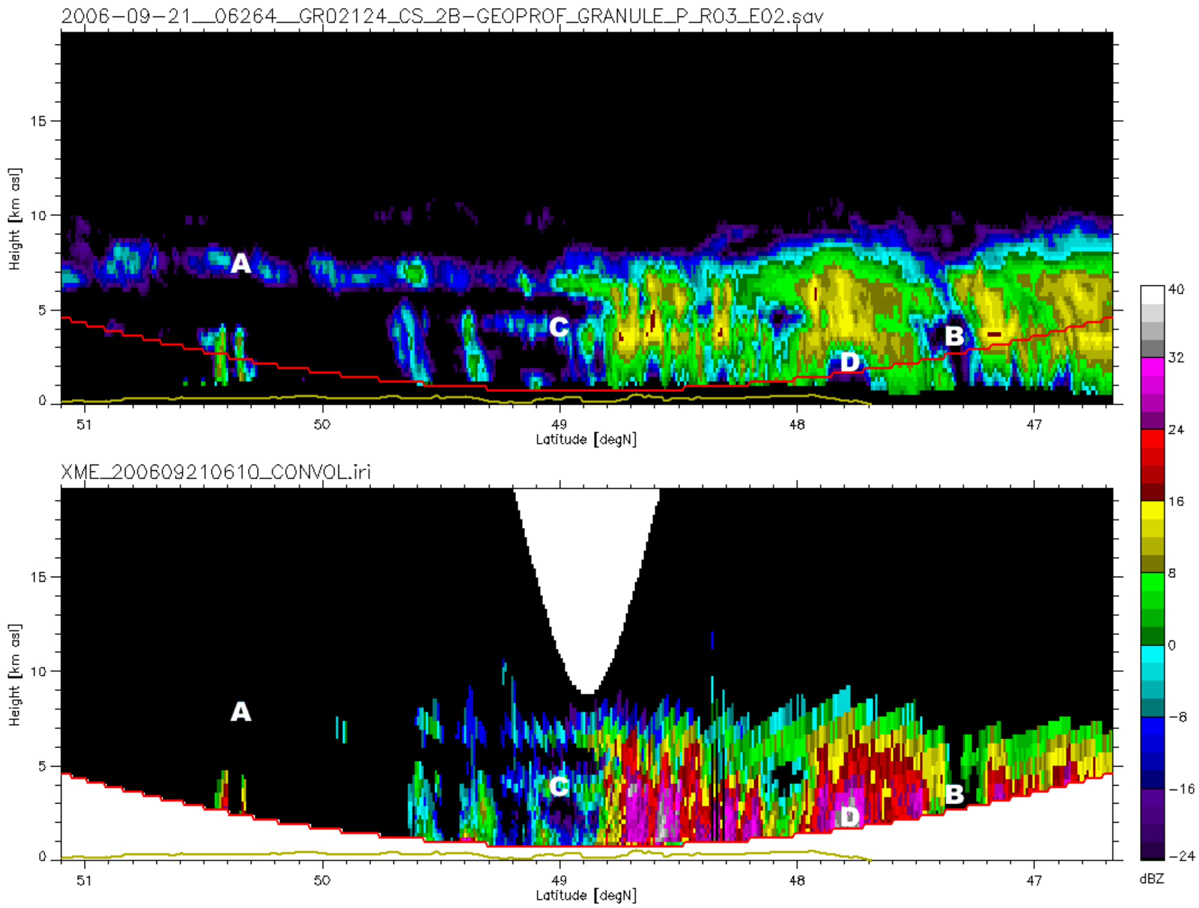

Figure 3: Reflectivity plot of 2006-09-21 case matched CloudSat swath and NRP CONVOL AVCS.
Matching features: A=missing cloud layer, B and C=consistent geometric cloud profile, D=storm cell attenuation

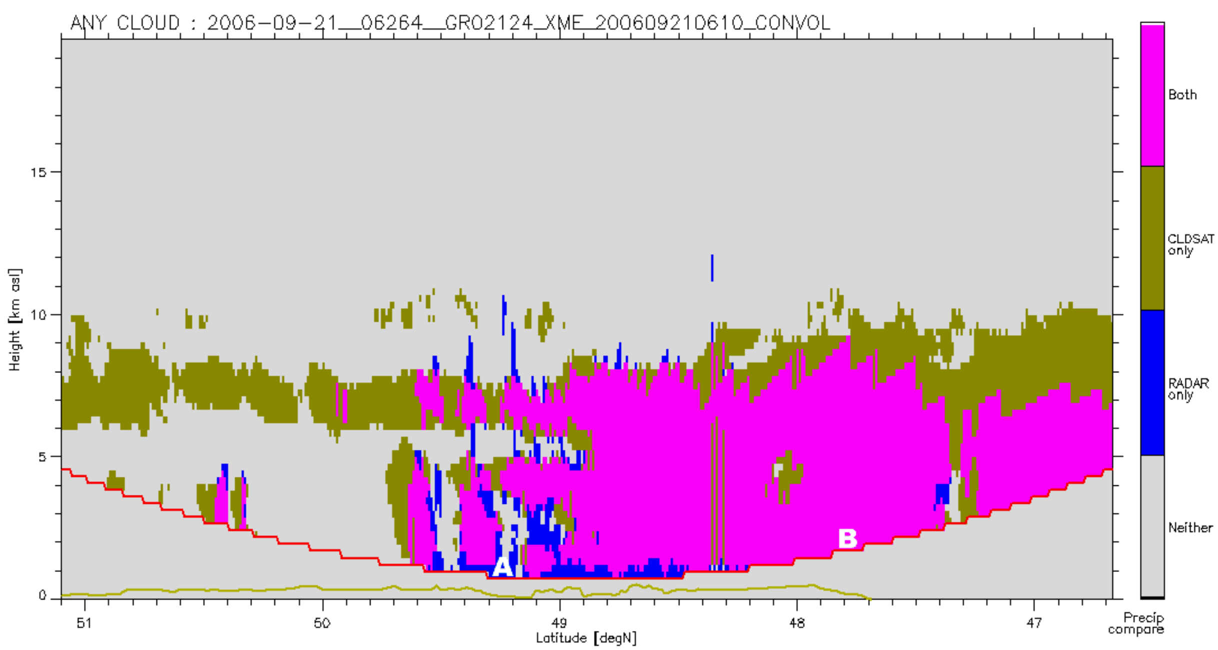

Figure 4: Cloud mask plot of 2006-09-21 case matched W-band CloudSat and ground based C-band NRP radar.
A = near surface echoes removed by CPR mask, B = preservation of echo mask despite strong attenuation.

All available vertical profiles for the Sep 2006 to Apr 2007 period were compiled into a fall/winter season dataset. This data set contains 1,166,565 vertical profiles scanned by the CPR. Categorical comparisons were then made, filtered by CloudSat results for cloud detection and precipitation occurrence.

Fig. 5 shows the echo occurrence for all 748,447 profiles with returns from either CPR or NRP AVCS. The probability curve shows that ground-based radar has detected a significant quantity of echoes on the underside of the CPR mask, below 1km. Therefore, there exist scenarios when the CPR is missing near-surface returns affecting the output of CloudSat algorithms trying to determine surface conditions (e.g. precipitation occurrence).

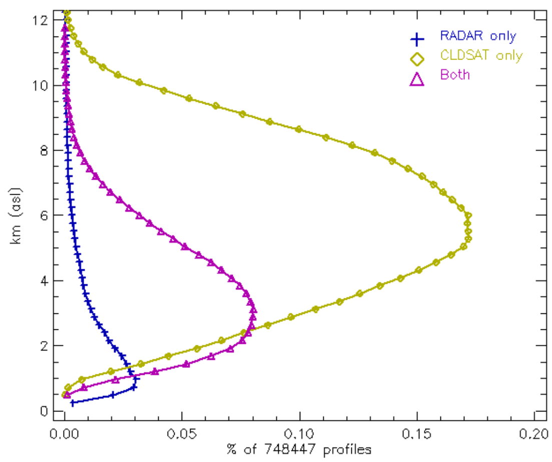

Figure 5: Echo detection distribution versus height for the 2006-07 fall/winter matching data set. Colours distinguish detection by CPR only, NRP ground radar only, and from both.

The distribution of reflectivity values below 2km for the matched CPR and NRP radars when precipitation occurrence is detected by the CloudSat algorithm is shown in Fig. 6. A valid match is defined as occurring only when both CloudSat and CONVOL echoes are present. This data set contained 358,082 matched profiles above the AVCS minimum height and under 2km, or ~30.1% of the total CloudSat scanned profiles. Fig. 6 yields some significant insights into the matter of attenuation and Mie scattering in precipitation rate algorithms.

Fig. 6 shows the distribution of reflectivity is dramatically different in precipitation scenes between the CPR and the NRP radar. The distribution peak reflectivity is shifted lower by 6dB. This highlights the effect of path attenuation at W-band and is therefore evidently an important issue to deal with.

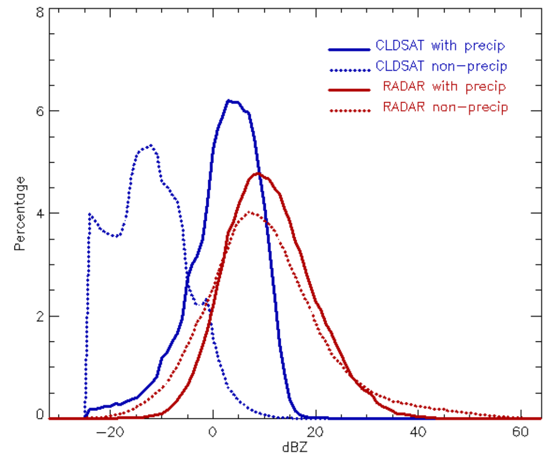

Figure 6: Histogram of reflectivity distribution for matched profiles below 2 kilometres above sea level. CPR's shown in blue as solid and dotted curves for CloudSat determined precipitating and non-precipitating scenarios respectively. NRP ground radar histograms are shown in red.

In fact, strong attenuation forms the basis for the next generation CloudSat precipitation rate algorithm (L'Ecuyer, 2002). Due to the effects of Mie scattering, reflectivities at W-band seldom exceed 20 dBZ and are more or less independent of rainfall rate above a few mm/hr. The gradient of observed reflectivity, attributable to attenuation, can be directly related to a rainfall rate.

5. FUTURE PLANS

A wealth of information from EC network is being collected on an ongoing basis for comparison with the CPR on CloudSat. Their analysis will facilitate addressing threshold definitions within the surface precipitation algorithm, and vertical sampling issues. At W-band, there are challenges for the CPR to discriminate cloud, drizzle, and light rainfall. Thus ground-based precipitation occurrence records will provide a critical role in assessing CloudSat algorithm's capture of the cloud to precipitation transition.

For example, there may exist, conditions in which the CPR misses precipitation perhaps due to either attenuation in intense precipitation or the masking of the near surface echoes in shallow clouds. Conversely, overestimation of precipitation may occur due to echoes detected by CPR that evaporate before reaching the surface (virga).

The POSS data will provide insight into particle size distributions and detailed precipitation rate information – useful in the development of a CloudSat precipitation rate algorithm product.

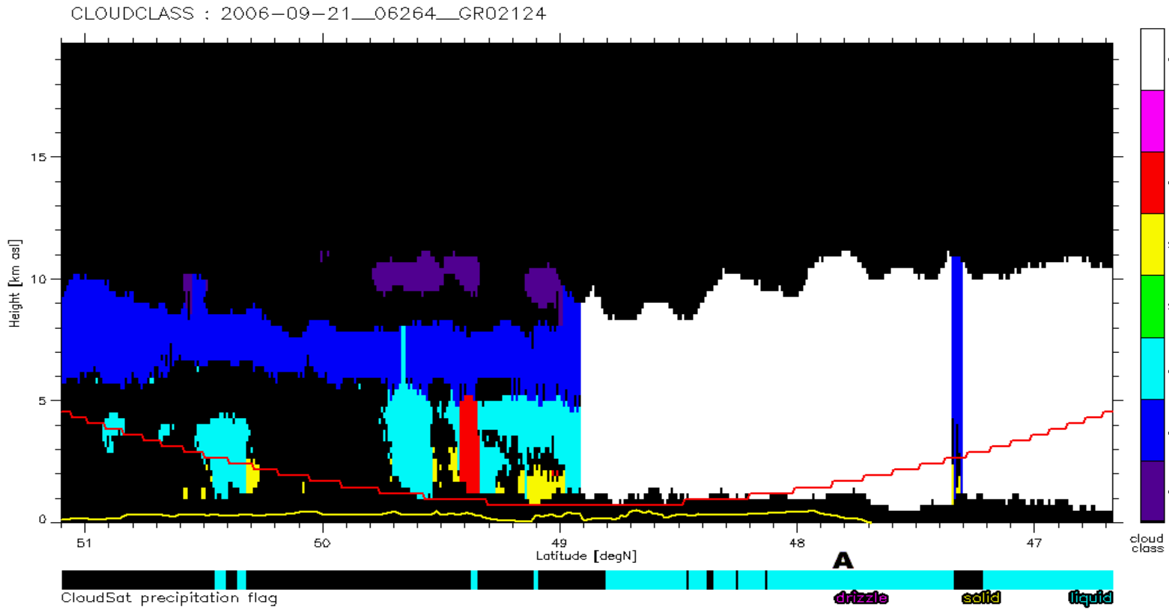

Figure 7: Cloud classification from CloudSat 2B_CLDCLASS product for 2006-09-21_XME case. CPR-based surface precipitation occurrence and type is shown as a coloured bar below the plot. Location A corresponds to the severe reflectivity attenuation as shown on Fig. 3 at location D

The other CloudSat product to be examined is the 2B-CLDCLASS cloud classification product (Stephens et al., 2002). It provides identification of following cloud types: Stratus (St), Stratocumulus (Sc), Cumulus (Cu), Nimbostratus (Ns), Altocumulus (Ac), Altostratus (As), Cirrus (Ci) and deep convection (Cb). Fig. 7 shows the complementary product for the 2006-09-21_XME case. Note at location A, despite the severe reflectivity attenuation as discussed earlier, the precipitation occurrence at the ground is properly identified.

Over Canada's higher latitudes, frozen precipitation cases will extend verification prospects to the experimental CloudSat discrimination of precipitation phase algorithm (as shown as the lower coloured bar in Fig. 7). Moreover, the EC POSS and the less attenuating C-band radar network can play an invaluable role in evaluating CloudSat models with respect to particle size distributions, attenuation from ice aloft and most importantly the melting layer.

The spread of the EC ground network of weather observing stations will be used to verify precipitation type and to help address the spatial representativeness of the CloudSat precipitation occurrence and cloud type product to a wider scale.

6. ACKNOWLEDGEMENTS

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