P4.11 USING CLOUDSAT DATA TO VALIDATE ICING PRODUCTS

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1. INTRODUCTION

CloudSat is part of the A-Train (Stephens et al. 2002), a group of polar orbiting remote-sensing instruments launched to provide detailed views of clouds and the atmosphere. It carries a cloud radar which provides a vertical profile of cloudy areas without any information about the cloud phase.

The NCAR Current Icing Product (CIP; Bernstein et al. 2005) produces hourly diagnoses of the probability and severity of aircraft icing conditions aloft over the CONUS and southern Canada. The CIP algorithm includes a scheme for identifying cloud tops and bases along with distinct cloud layers. It is based on a combination of model data with observations from satellite and surface stations. Validation of this scheme has been difficult in the past because of a lack of observational truth data. Pilots seldom report cloud tops and bases and information on cloud layers, and existing reports can be unreliable.

CloudSat provides regular observations of cloud layers that can be used to validate cloud top algorithms (as in Weisz et al. 2007). CIP tends to be overly conservative in cloud top estimation, especially at low altitudes, resulting in higher cloud tops than those observed and a greater volume of icing-warned airspace than in reality. This paper will compare cloud top heights measured by CloudSat to those derived by CIP in case studies. Some initial statistical analyses will also be presented.

2. DATA

2.1 Current Icing Product (CIP)

CIP currently uses a combination of satellite and model data to identify the cloud top. In cloudy areas the cloud top height (CTZ) algorithm compares the temperature measured at the top of the cloud by the infrared sensor to a model sounding (CIP uses the Rapid Update Cycle, or RUC as model input). Because the horizontal resolution of CIP is 20 km and the satellite data from GOES is 5 km horizontal resolution there are up to 16 pixels of satellite data for every CIP point. The infrared temperatures from the cloudy pixels are sorted and the 90th percentile coldest is used as the cloud top temperature for the entire CIP grid point. The cloud top height is then set to one model level above where the model temperature first becomes warmer than the cloud top temperature (Bernstein et al. 2005).

2.2 CloudSat

The cloud profiling radar (CPR) on CloudSat operates at 94 GHz. Backscatter from cloud and precipitation-sized particles is converted into a reflectivity value. With its -28 dBZ minimum detectable signal, the CPR is able to detect most clouds, except those that are very thin or those that are made up of very small particles, which are too small for the radar to sample. It provides reflectivity data every 240 m from the surface to 30 km along the nadir track (Stephens et al. 2002).

For this study the CloudSat CTZ was derived by finding the altitude at which the first two valid (≥ -28 dBZ), concurrent reflectivity values occurred when working down from the top of the retrieval. If there was one valid value followed by a missing value (< -28 dBZ) then that level was not considered to have a cloud of interest. In this case the search for a cloud top continued on to lower altitudes. This requirement guaranteed that only clouds with a depth near or above 500 m were considered. Due to the presence of ground clutter cloud tops were not considered within 1.5 km of the surface.

3. METHODOLOGY

Because the spatial and temporal resolutions of the datasets are quite different some smoothing was necessary. First, the datasets needed to be matched in time. CIP is run hourly, while the CloudSat CPR measures reflectivity

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every 0.16 s (Stephens et al. 2002). For this study all of the CloudSat measurements within a half hour of the CIP valid time were matched to the CIP CTZ. For example, CloudSat data between 1730 and 1830 UTC were matched to CIP CTZ output with a valid time of 1800 UTC.

The fast sampling rate of CloudSat results in many measurements of reflectivity potentially being taken within the same CIP grid area (20 km horizontal resolution). To find good matches between the datasets the total number of observations from CloudSat that occurred within each CIP grid point were counted. If at least 75% of those observations contained a valid cloud (i.e. two concurrent reflectivity measurements in the column above 1.5 km) then that grid point was considered cloudy. This decreased the amount of broken clouds in the dataset, which CloudSat would have no trouble observing but CIP may not be able to diagnose with its coarser resolution. The median CTZ from the CloudSat measurements was then compared to the corresponding CIP CTZ for that grid point. This was done for all CloudSat passes over the CIP domain between January and March 2007, which resulted in over 38,000 matches.

4. CASE STUDIES

4.1 Canadian CloudSat/CALIPSO Validation Project (C3VP)

Before the CPR can be considered to be truth data in a comparison with CIP a comparison between its measurements and an actual cloud top observation should be done to determine if the technique and data are suitable for such a comparison. The C3VP (http://www.c3vp.org) is an ongoing program focused on validating measurements from CloudSat and CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) using ground-based and airborne instruments. The latest IOPs for this project were from October 2006 through March 2007 and included research flights by the NRC Convair 580 along the satellite track. On 5 November 2006 both the aircraft and the CPR sampled an area of solid clouds over southern Ontario. This is a good case to compare because wintertime continental stratus decks are usually not highly variable, meaning that there could be a larger separation in the timing of the observations without hurting the comparison. There were two cloud top penetrations by the Convair along the satellite track and within an acceptable time of the satellite overpass on this day. The CloudSat trace (Figure 1) through the test region shows clouds with solid tops around 4500 m along with a few higher clouds. The Convair sampled the tops of the lower layer only.

CloudSat sampled the exact locations of the Convair penetrations within 35 minutes (Table 1). For Cloud Top 1 the CloudSat CTZ was 290 m (950 ft.) too low. This is close to the vertical resolution of the CPR (240 m), which will be used as the accepted range of differences in the overall comparisons in Section 5. The CTZ values were almost identical for Cloud Top 2. Both the Convair and CloudSat observed consistent cloud tops with little variation in their heights. The good agreement between the two observations in this case gives confidence that the CloudSat can be used as a reasonable representation of the actual cloud top.

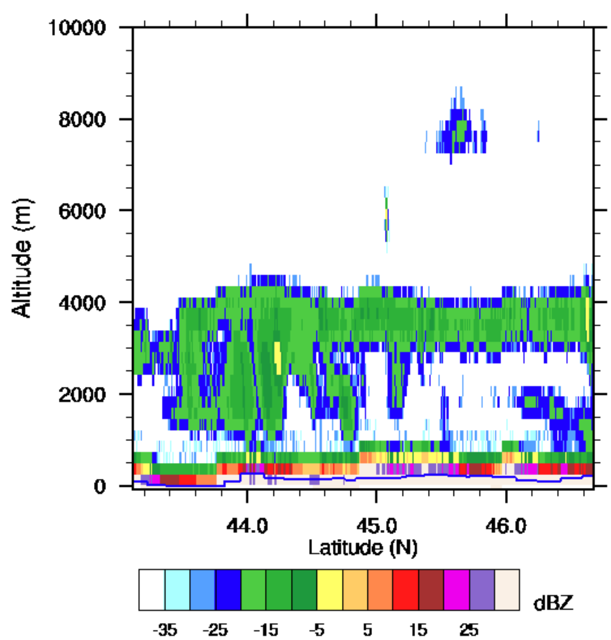

Figure 1. CloudSat radar reflectivity cross-section from 2028 – 2029 UTC on 5 November 2006. The blue line represents topography.

	Cloud Top 1	Cloud Top 2
Aircraft Cloud Top Time (UTC)	1857	1903
Aircraft CTZ (m)	4560	4596
CloudSat Sample Time (UTC)	1829	1828
CloudSat CTZ (m)	4250	4580
CTZ Diff. (m)	290	16

Table 1. Aircraft and CloudSat CTZ observations and sampling times for two locations.

4.2 20 January 2007

On this date CloudSat passed over the western U.S. and Mexico (Fig. 2) between 2025 and 2036 UTC. The focus will be on the track segment over the southern part of the domain in Fig. 2 (red part of the line; 2025 – 2031 UTC), where the 2000 UTC CIP CTZ analysis shows a variety of cloud top heights.

Figure 3 shows the CPR cross section with the CIP CTZ overlaid. The CloudSat trace verifies the presence of clouds with a large range of top heights. CIP generally follows the radar cloud tops but performs better in some areas than others. In the south (near 21 °N) the CPR observed some patchy clouds, while CIP has a continuous cloud. CIP is more likely to have a smoother cloud field because of its coarser resolution. As the cloud tops initially increase in height (21.5 – 22 °N) the CIP trace follows nicely. However, when the tops decrease in height shortly after that and remain low (22 – 24.5 °N) the CIP CTZ remains too high. This is a common problem in CIP, especially for lower clouds, because the present CTZ scheme is completely reliant on the model temperature and may be fooled by strong inversions at cloud top. Starting at 24.5 °N the system deepens substantially, and the CIP CTZ again follows the corresponding increase in top height. For the highest clouds (25.5 – 28 °N) CIP again slightly overdoes the CTZ, but both sets of observations show the cloud ending in almost the exact same place.

CIP appears to begin diagnosing clouds again before CloudSat (30 °N), but it is difficult to tell if the echo near the surface is due to clouds or if it is noise. An argument could be made either way, but since it is within 1.5 km of the surface it will be ignored anyway. However, Stephens et al. (2002) state that CloudSat misses up to 40% of low-level boundary layer clouds over land, of which type this cloud almost certainly is. The lower clouds from 31 – 33 °N are well represented by CIP, in contrast to the previous batch of low clouds.

From 33.5 °N to the end of the trace the clouds become quite complex with highly variable cloud tops and layers. Around 35 and 37 °N CloudSat shows a two-layer situation that CIP appears to miss. Here, the CIP CTZ trace is in the area with no clouds and appears to be following the decreasing altitude trend of the lower layer. The CIP CTZ gets back on track once a single cloud layer is present again. Between 37.5 and 38.5 °N the upper layer dissipates, and CIP does well in showing the hole that has opened up there.

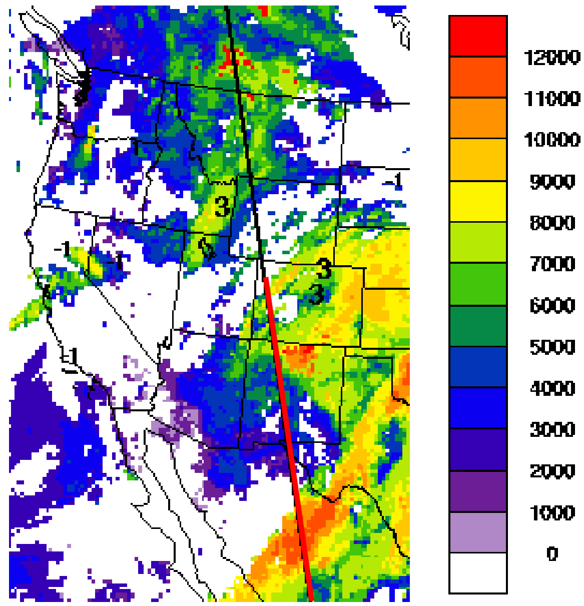

Figure 2. CIP CTZ (m) analysis for 2000 UTC on 20 January 2007. The line represents the CloudSat track. The numbers show locations and severities of icing PIREPs (-1 = no icing, 3 = light icing).

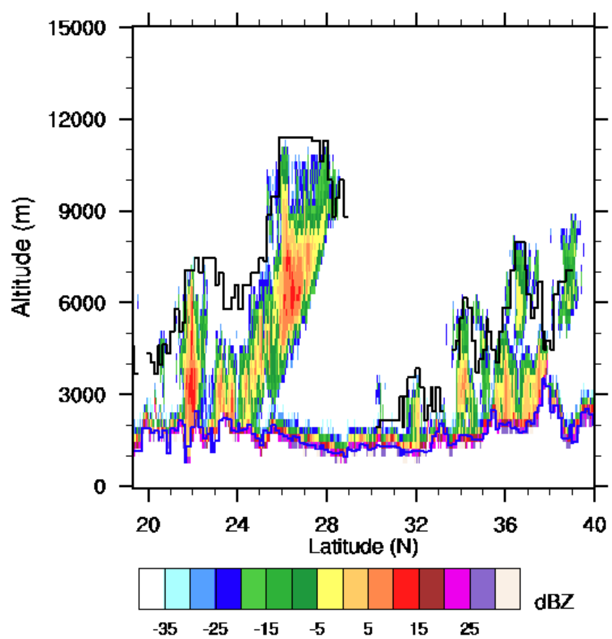

Figure 3. As in Fig. 1 but for 2025 – 2031 UTC on 20 January 2007. The matching CIP CTZ values are shown with the black line.

5. COMPARISONS

CIP and CloudSat did not always agree on the presence or absence of a cloud. 73% of the grid points where CloudSat observed a cloud also contained a CIP cloud. Reasons for the discrepancies include, but are not limited to: bad or missing satellite data in CIP; high, thin cirrus that were observed by CloudSat but not CIP; and time latency issues such as clouds showing up in CIP but moving before the CPR pass. This section will focus on the 38,000+ grid points where both datasets agreed on the existence of a cloud.

The average difference in CTZ was -327 m, which means that, on average, the CIP CTZ was 327 m *lower* than the CloudSat-measured value. This difference is close to the accepted CPR range of ±240 m (±1 range gate). Points where the CIP CTZ was lower than the CloudSat CTZ (by 240 m) were actually the most represented in the dataset. 48% of the total matches fell into this category, compared with 37% that had a higher CIP cloud top and only 15% where they were within 240 m of each other.

This distribution and average difference, while representative of the entire dataset, varies with the cloud top height. Figure 4 shows the difference distributions for cloud top heights (from CloudSat) < 3 km, 3 – 6 km, 6 – 9 km, and > 9 km. The average difference for each of these bins is also indicated. For the lowest clouds (Fig. 4a) the vast majority of the differences (85%) are greater than 240 m (light blue bars), meaning that CIP tends to over-diagnose the tops of these clouds. As the altitude of the cloud tops increases, though, the distribution shifts to an under-diagnosis of CTZ by CIP. For cloud tops above 9 km (Fig. 4d) 70% of the differences are now less than -240 m (red bars). The average difference also reflects this for each altitude level, going from 1405 m for the low clouds to -827 m for the highest ones. The upper mid-level clouds (6 – 9 km; Fig. 4c) have the lowest average difference (-443 m) and the highest percentage of points between -240 and 240 m (green bars).

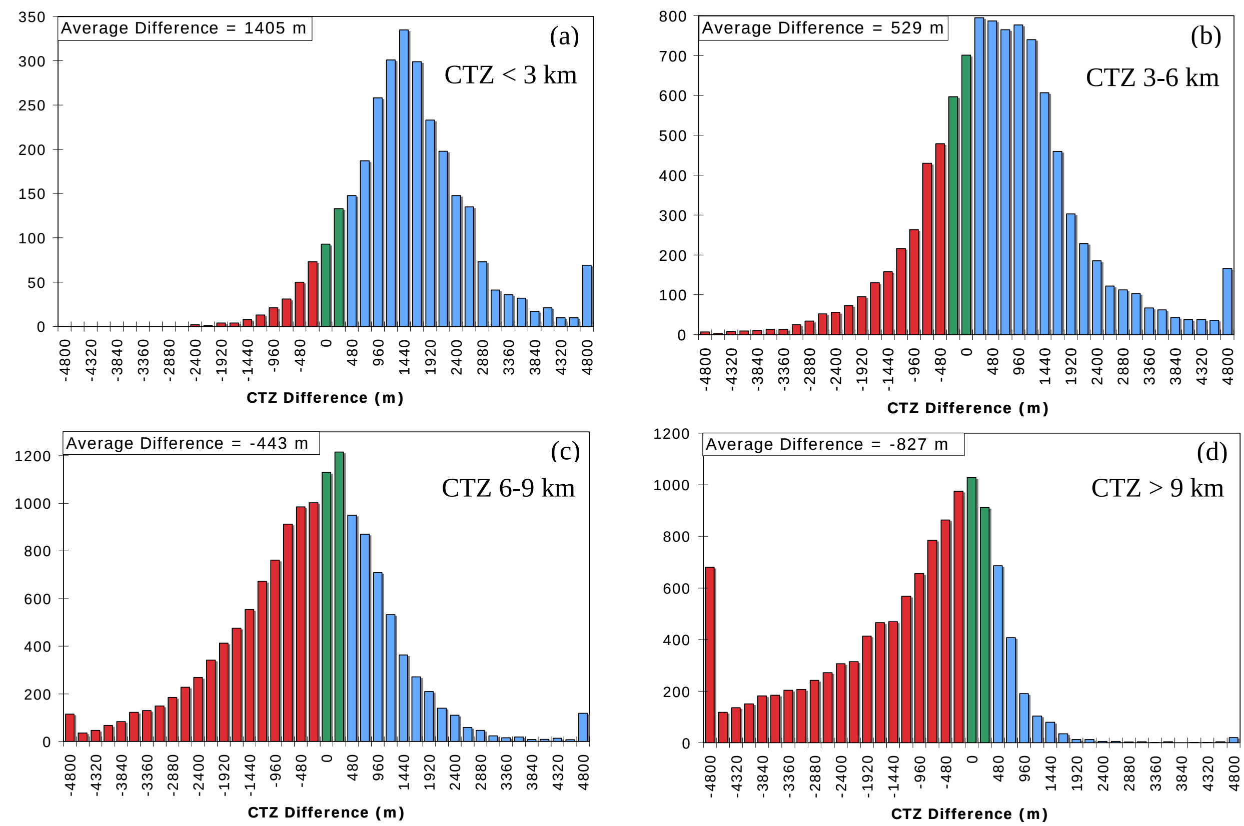

Figure 4. Distribution of differences between CIP and CloudSat CTZ observations (in meters) for CloudSat measured cloud tops with heights (a) < 3 km, (b) 3 – 6 km, (c) 6 – 9 km, (d) > 9 km. Red bars represent differences less than -240 m, green bars represent differences between -240 and 240 m, and blue bars represent differences greater then 240 m. The average difference for each bin is in the upper left corner of the plots.

6. DISCUSSION & FUTURE WORK

In general CIP appears to have cloud tops that are too high for low-altitude clouds and too low for high-altitude clouds. The over-diagnosis at low altitudes is expected. Comparisons with research aircraft data have shown that CIP often overestimates the CTZ when a strong inversion is present, which is common in low-level wintertime clouds (e.g. a post-cold frontal stratus layer). The strength of the inversion is often underdone in the RUC model, which results in a CTZ that is too high, since the satellite observed CTT is only found in the model temperature sounding well above the inversion.

The shift to diagnosing lower tops than observed at higher altitudes is a bit surprising, but the developers have never compared high altitude cloud top penetrations with CIP CTZ. This error decreases the cloud volume in CIP, but does not result in a decrease in the icing volume, mostly because CIP does not diagnose icing near the tops of these clouds. The minimum temperature for icing in CIP is -25 °C, except in convection, where it decreases to -30 °C. Therefore, the effect on CIP's icing diagnoses is quite small. The error is likely due to either poor model forecasts of temperature at upper levels or the semi-transparent nature of cirrus, whereby the satellite brightness temperature is contaminated (higher than the physical temperature of the cloud top) by radiances from warmer clouds/surface below.

A new CTZ algorithm has recently been developed for CIP that seeks to improve the cloud top height diagnosis by using fuzzy logic to combine interest maps of the median cloud top temperature (instead of the 90^{th} percentile) measured by the satellite over the CIP grid point with interest maps of other model fields such as θ_e, condensate, relative humidity, and vertical velocity. This new method has shown to reduce the icing volume without sacrificing CIP's skill at detecting positive icing. It is currently being run internally, and the CloudSat data will be used to gauge its accuracy and determine if it decreases (increases) the diagnosed CTZ at low (high) altitudes. The CTZ algorithm in the Forecast Icing Product (FIP) will undergo a similar validation.

CloudSat is also good at cloud layer identification (Section 4.2 and Lee et al. 2007) and can be used to help validate the layer schemes in CIP and FIP, which has never been done.

Plots showing the reflectivity from CloudSat with the CIP CTZ overlaid are also being created at NCAR. They can be found at http://www.rap.ucar.edu/icing/cloudsat. These images will be examined over the winter to identify scenarios where improvements can be made.

7. REFERENCES

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