3.3 THE CANADIAN CLOUDSAT CALIPSO VALIDATION PROJECT:EVALUATION OF SENSITIVITY AND SUB-PIXEL VARIABILITY OF CLOUDSAT DATA PRODUCTS

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1. INTRODUCTION

The Canadian CloudSat CALIPSO Validation Project (C3VP) aims to evaluate data products from CloudSat and CALIPSO over Canada. The focus of the work deals with cold season cloud systems. This is seen as a necessary first step before using the CloudSat data products in weather and climate applications over Canada and cold climates in general.

The overall strategy of C3VP is summarized in Hudak et al. (2006). It employed targeted field campaigns with a cloud physics aircraft operating in the vicinity of an enhanced ground measurement site. In addition, it makes use of observations from Environment Canada's weather observing network. This permitted both the acquisition of an independent suite of cloud and precipitation products for statistical evaluation and the means to test the assumptions inherent in the CloudSat data product algorithms. This is summarized in Fig. 1. Rodriguez et al. (2007) discuss the network approach. In this paper, data collected by the cloud physics research aircraft are considered.

Stephens et al. (2002) suggested that the radar onboard CloudSat (CPR), with an expected minimum detectable signal of -28 dBZ, would be able to detect 90-95% of radiatively significant ice clouds and up to 80% of the water clouds. Boundary layer clouds and cirrus are expected to the most difficult to observe. In support of Stephens et al. (2002) assessment of ice cloud detection, Hudak et al. (2004), using radar data collected in Canada's Northwest Territories, estimated that CloudSat's radar would detect 94% of the cloud occurrence correctly. But Hudak et al. (2004) noted that biases can be expected in cloud thickness and cloud layering as a result of the 480 m vertical resolution of the CloudSat radar measurements. Data from aircraft in C3VP will be used to evaluate radar sensitivity, validate cloud profile products and detection, and assess the effect of sub-pixel variability on these products.

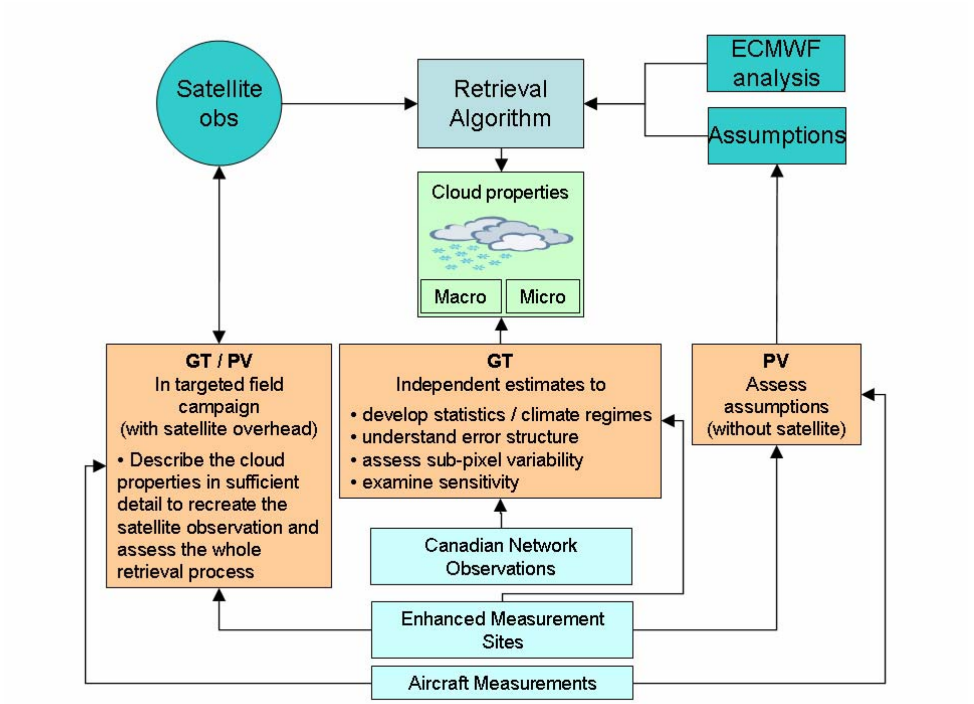

Figure 1: A summary of the validation strategy for C3VP incorporating ground truth (GT) and physical validation (PV).

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2. OVERVIEW OF C3VP

The aircraft component of C3VP involved under-flights of CloudSat by a Convair-580 research aircraft operated by the National Research Council of Canada (Hudak et al., 2006). The instrumentation on the aircraft included a full suite of in-situ cloud, precipitation and aerosol sensors. Also on the aircraft were two radars, one a dual frequency W/X-band and the other Ka-band, and a dual-channel lidar. This gives similar, but enhanced, capabilities with respect to sensitivity and vertical resolution as compared to the radar and lidar onboard CloudSat (Stephens et al, 2002) and CALIPSO, respectively.

The aircraft operational period consisted of flights during four two-week periods between late October, 2006 and early March, 2007. The flight strategy entailed flights beneath the satellites during overpasses in south-central Canada. Figure 2 displays CloudSat's ground-tracks within the 16-day orbital cycle that were selected as candidate overpasses, taking into account the logistics of the aircraft location (YOW) relative to the enhanced measurement site (CARE) and aircraft range.

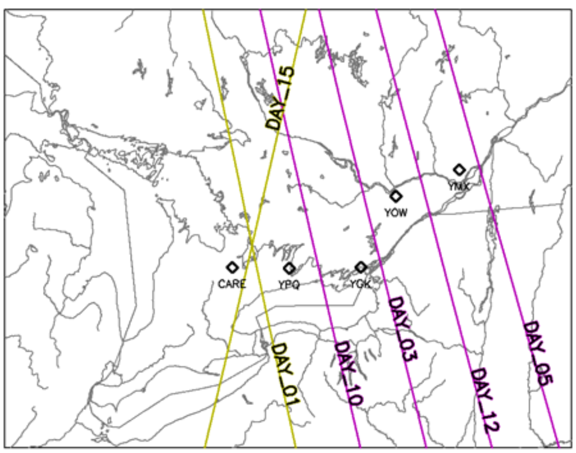

Figure 2: Satellite tracks that were candidates for under-flights by the research aircraft. Adjacent orbits are approximately 120 km apart. The aircraft was housed in Ottawa (YOW) and the enhanced measurement site was located at CARE. Day numbering is relative within the 16-day orbital cycle.

The possible cases included five ascending orbits (~1830Z) and one descending orbit (~0730Z). The goal during each two-week intensive operating period (IOP) was to fly on five of the possible six orbits. The aircraft operated within a 30 nm radius circle centered on the satellite track at a point selected during the pre-flight weather briefing. Satellite track estimates were made on a daily basis using the latest Two-Line Element parameterization file. The general flight strategy was to have the aircraft at, or, near cloud top 30 min before satellite overpass, and then perform vertical-profiling of the cloud systems or multiple transects along the track at various altitudes for an additional hour following overpass.

Table 1 summarizes twenty-one successful under-flights of CloudSat that were made during C3VP. In general, there were: 9 cases of multi-layer mixed phase clouds, both frontal and non-frontal; 2 nimbostratus snow cases; 2 lake-effect snow cases; 4 cases of low clouds; 2 cases of cirrus; and 2 cases of clear skies. In five of the flights, aerosols were a prominent focus of the mission.

C3VP Flight Summary	
Date	**Characterization**
2006/10/31	Mixed phase multi-layer-frontal (warm)
2006/11/03	Lake-effect squalls
2006/11/05	Multi-layer, mixed phase, non-frontal
2006/11/07	Multi-layer, embedded convection
2006/11/09	Multi-layer, embedded convection, frontal (cold)
2006/11/30	Multi-layer, mixed phase, post cold frontal clouds
2006/12/2	Nimbostratus - snow
2006/12/5	Low cloud, non-frontal
2006/12/7	Lake-effect, low clouds
2006/12/9	Mixed phase Multi-layer, non-frontal
2006/12/11	Low clouds - liquid
2007/01/19	Multi-layer mixed phase, non frontal
2007/01/22	Nimbostratus - snow
2007/01/24	cirrus
2007/01/26	Aerosols
2007/01/28	Aerosols and low clouds
2007/02/18	Aerosol and low clouds
2007/02/20	Multi-layer, mixed phase, frontal (warm)
2007/02/23	Aerosols
2007/02/25	Multi-layer, mixed phase, frontal (warm)
2007/02/27	Aerosols and cirrus

Table 1: A characterization of the 21 cases flown beneath CloudSat.

3. RESULTS

The most common cloud occurrence encountered was multi-layered cloud systems. One such case on November 5, 2006, reveals some of the challenges related to the inference of cloud properties from CloudSat radar data.

Figure 3 shows CloudSat CPR data in an 80 km section over the study area. A layer of altocumulus with tops at approximately 4500 m with virga beneath was detected. Maximum reflectivities were around -6 dBZ. There is also a suggestion of some cirrus above, visible from the aircraft, with some scattered pixels near the minimum detection limit of the CPR.

Figure 4 displays corresponding aircraft Ka-band radar data. The aircraft was flying straight and level at an altitude of about 6100 m asl. Qualitatively, the reflectivity patterns in Figs. 3 and 4 are very similar. The Ka-band radar displays a finer scale cellular structure with larger core reflectivities. There is also a less extensive area of virga below.

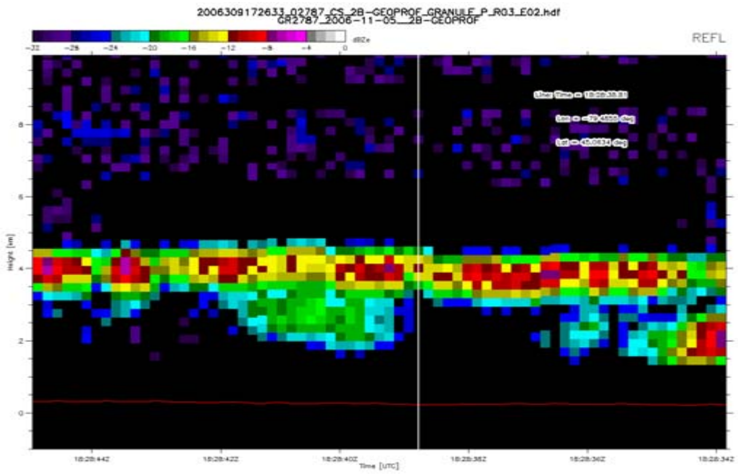

Figure 3: CloudSat CPR data on November 5, 2006, for ~80 km over the area of operations of the research aircraft. The vertical white line corresponds to the instant CloudSat passed overhead the aircraft.

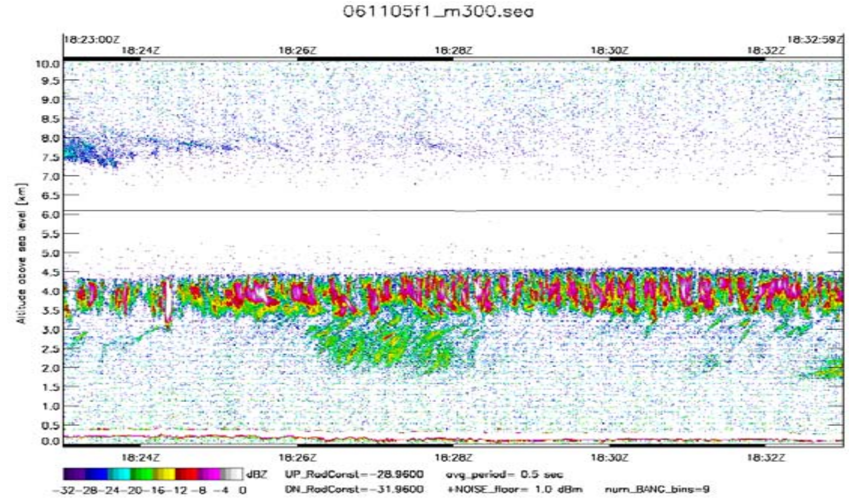

Figure 4: Reflectivity data from the Convair Ka-band on November 5, 2006 for the same horizontal extent as Fig. 3.

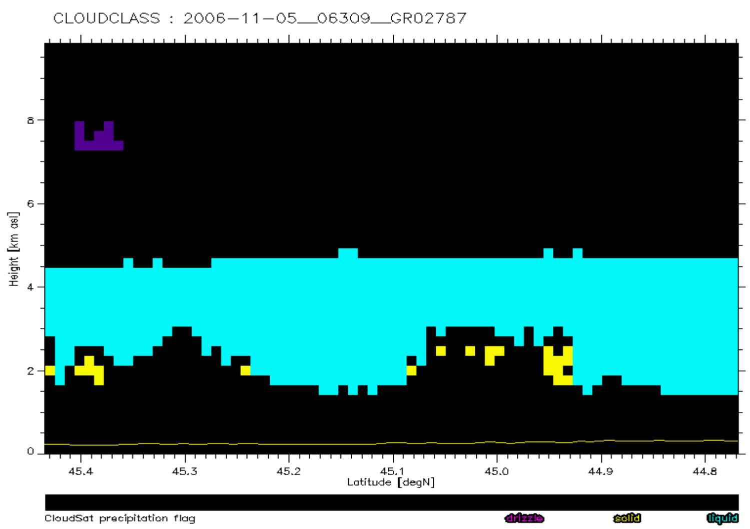

Figure 5: CloudSat cloud type, precipitation occurrence, and precipitation product corresponding to Fig. 3.

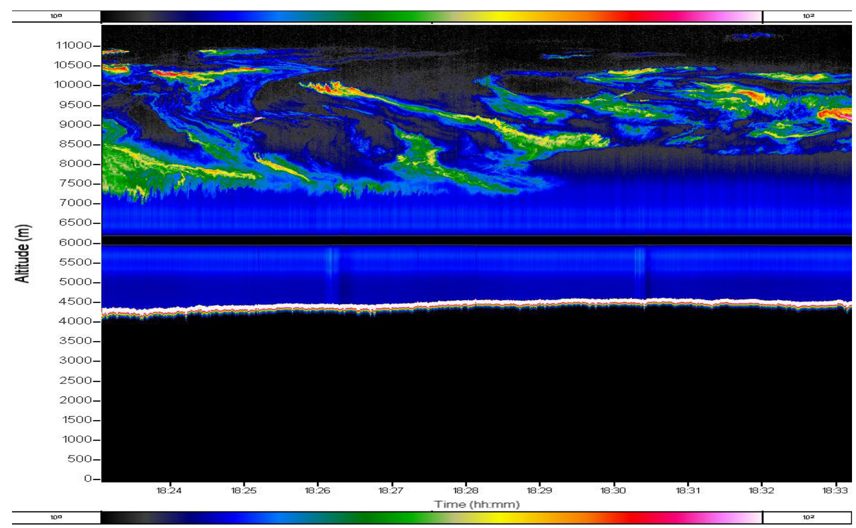

Figure 6: The 532 nm backscatter from the Convair dual-channel lidar on November 5, 2006, for the same time period as Fig. 4.

Figure 5 gives cloud type and precipitation occurrence product inferred from CloudSat data shown in Fig. 3. The product correctly identifies the layer of altocumulus, a small patch of cirrus, and no precipitation. The average thickness of the altocumulus is ~2000 m, whereas from the Ka-band aircraft data, it is ~1000 m. The coarser vertical resolution of the CloudSat data is responsible for this overestimation of cloud vertical extent.

Additional details of the cloud structure are provided by the aircraft onboard lidar (Fig. 6). It is apparent that there was upper level cirrus that was below the detection limit of both the CPR and aircraft Ka-band radars, except for a small patch from 7.5 km to 8.0 km at the northwestern edge of the track. The second noteworthy item is the high lidar signal at the top of the altocumulus layer with complete attenuation about 200 m into the cloud, a clear indication of a liquid water layer there.

Once the satellite had passed, the aircraft descended to the top of the altocumulus layer. Porpoising maneuvers were done from cloud top to cloud base along the satellite track. The Ka-band radar indicated that the character of the radar echo had not changed significantly from the time of overpass. Figure 7 displays selected aircraft data during this period. The horizontal lines in the top panel indicate the extent of the visible cloud defined by the liquid cloud droplets, which was ~500 m thick. The aircraft profiled the cloud three times. Liquid water contents (LWC) ranged from near zero at cloud base to 0.25 g m^{-3} near cloud top. Ice water content (IWC) was very low (<0.005 g m^{-3}).

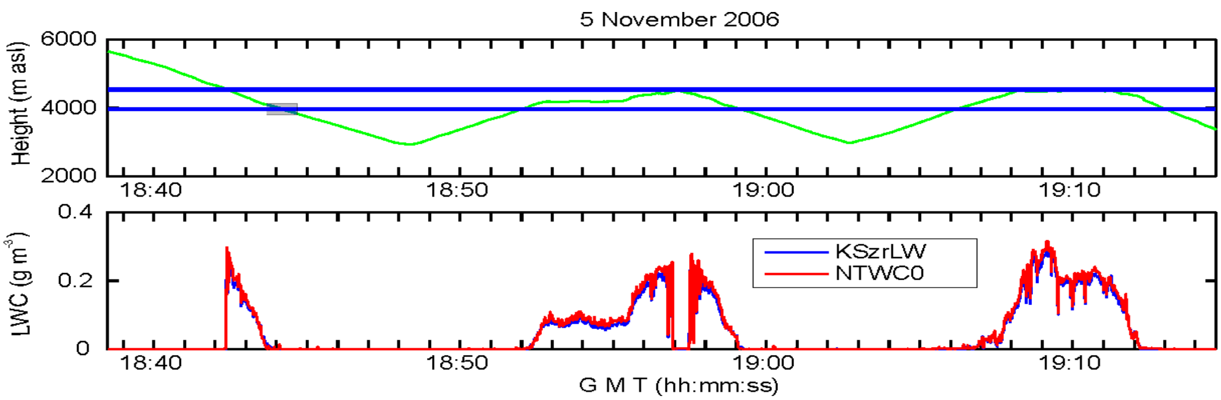

Figure 7: Convair data during porpoising maneuvers on November 5, 2006. The top panel is aircraft altitude and the bottom plot is liquid water contents derived from the PMS King probe (KSzrLW) and the Nevzorov LWC/TWC system (NTWC0). The parallel lines in the top panel correspond to the extent of the visible cloud layer.

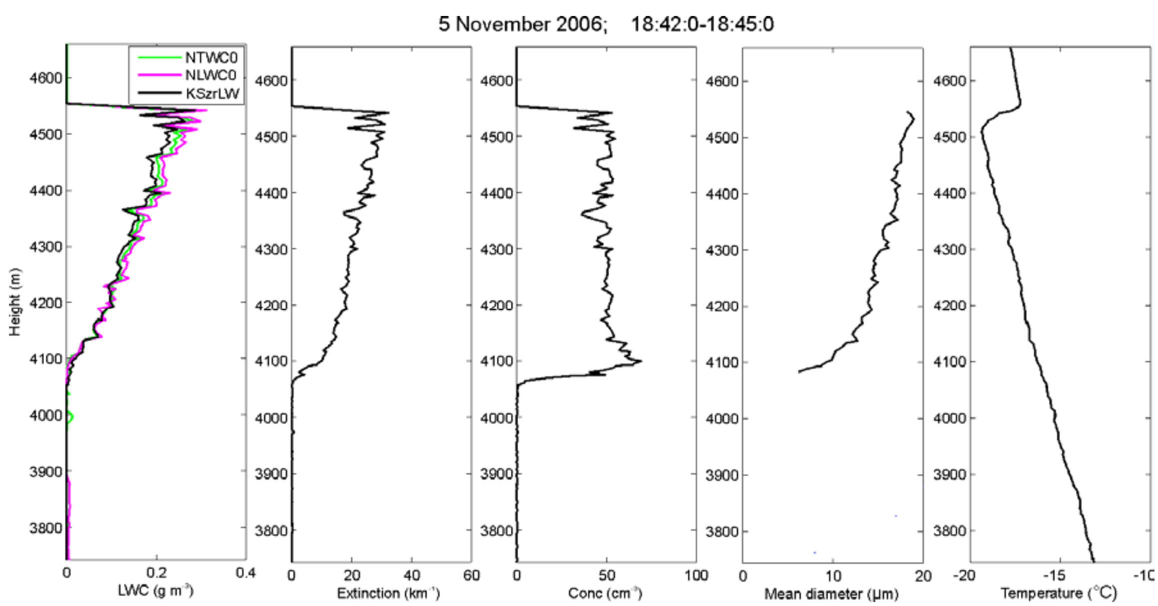

Figure 8: Convair vertical profiles for several in-cloud parameters corresponding to Fig. 7, from left to right: LWC, extinction, droplet concentration, average droplet diameter, and temperature. Extinction, droplet concentration, and average droplet diameter panels were derived form measurements from the FSSP96 (3 to 45 µm size range).

Figure 8 gives the vertical profile of LWC, extinction derived from measurements of droplet size and concentrations, droplet concentrations, mean droplet size, and temperature during the first cloud profile of the aircraft. This shows a near steady increase in liquid water content, extinction, and mean droplet size from cloud base to cloud top with a relatively constant droplet number concentration. The associated reflectivity from droplets was below the minimum detectable signal of both the CPR on CloudSat and the Ka-band radar on the aircraft. Temperature near cloud top, where LWC was 0.25 g m^{-3}, was approximately -19°C.

The CloudSat-derived LWC and IWC profiles during the overpass are given in Fig. 9. The LWC amount increases from cloud top to cloud base, in direct contradiction to the aircraft measurements (Fig. 8). Also, CloudSat's IWC values are substantially larger than the aircraft measurements (not shown).

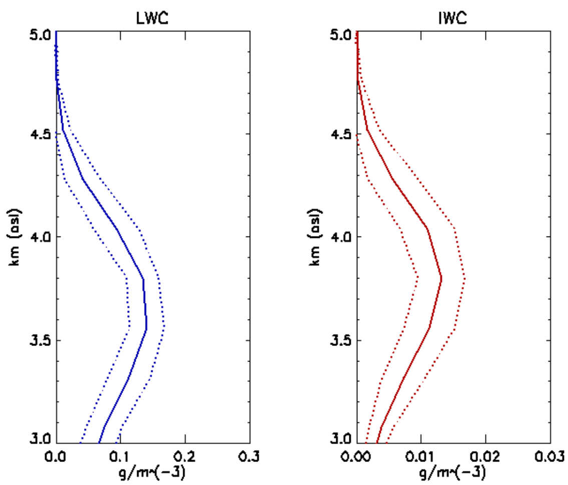

Figure 9: LWC and IWC profiles (mean and standard deviation) corresponding to CPR data shown in Fig. 3.

Figure 10 gives some sample images from the PMS 2D probes on the aircraft. Sample times are indicated by the shaded box in the top panel of Fig. 7. There were low concentrations of rather large dendritic crystals, some significantly rimed near and below cloud base. The mass content was small, but their associated radar reflectivity, because of their relatively large size, was sufficient to be detected by both CloudSat's and the aircraft's (Ka-band) radars. In effect, this cloud had the combination of significant amounts of liquid water in droplets too small to be detected by the radar together with a small number of sufficiently large ice particles that could be detected but had negligible mass. The result is an erroneous characterization of the microphysical properties by the CloudSat algorithms.

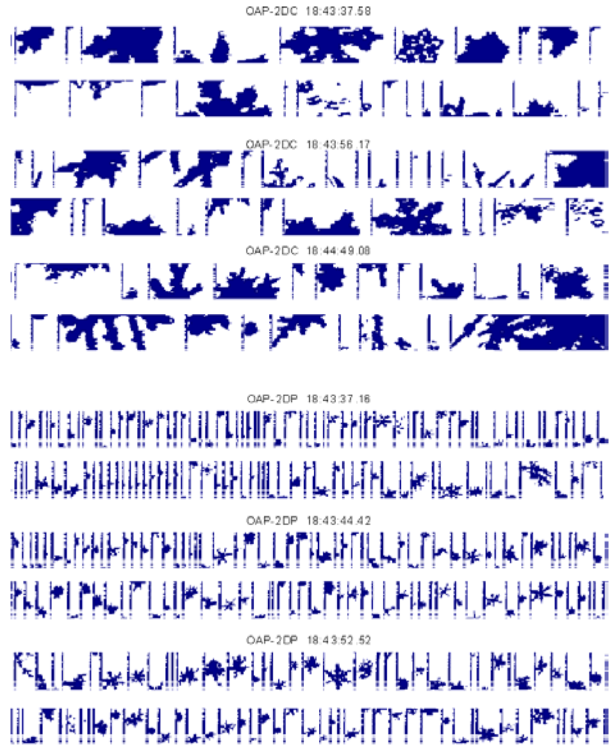

Figure 10: Upper six sample images are from the PMS 2D-C (vertical scale: 800 µm) while the lower 6 are from the PMS 2D-P (vertical scale: 6400 µm) during the time period depicted by the shaded box in the top panel of Fig. 7.

4. SUMMARY

The aircraft component of the Canadian CloudSat-CALIPSO Validation Project gathered detailed microphysical data under a wide variety of cold-season cloud conditions. Twenty-eight missions were flown, twenty-one timed to the passage of CloudSat, thereby totaling 107 flight hours. Many of these flights took place in the vicinity of the enhanced ground measurement site at CARE to further expand the possibilities for independent ground truth and physical validation of CloudSat data products.

The Nov. 5, 2006 case that was documented here, of a mixed-phase cloud layer with liquid drops near cloud top and snow and ice below, sublimating before reaching the surface represents a common scenario in the Great Lakes-St. Lawrence Lowlands. Very similar conditions have also been documented in many other locales including the Arctic (Pinto, 1998, Fleishauer et al., 2002), and form an important cloud scenario. CloudSat products associated with macroscopic characteristics such as cloud type and precipitation occurrence perform well. There was a significant overestimation, however, of cloud vertical extent. The cloud mask from CloudSat depicted a 2000 m thick cloud layer. The aircraft in-situ measurements, taken some 15 min later but under similar conditions according to the Ka-band radar, showed the vertical cloud extent to be only 500 m. The profiles of other microphysical properties such as LWC and IWC, based solely on radar measurements, are inadequate. Futhermore, only the lidar sensed the upper-level cloud with any credibility.

Additional information from other satellites in the A-train (Stephens et al., 2002) and more sophisticated algorithms are required to correctly characterize this type of cloud scenario. Detailed analyses of aircraft microphysical data (e.g., Fig. 8) when combined with the EarthCARE simulator (Hudak et al., 2006) will help ensure a consistent framework for the testing of refined approaches.

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