P12A.8 NASA GPM/PMM PARTICIPATION IN THE CANADIAN CLOUDSAT/CALIPSO VALIDATION PROJECT (C3VP): PHYSICAL PROCESS STUDIES IN SNOW

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1. INTRODUCTION

A complete understanding of the Earth's hydrologic cycle necessarily dictates an ability to accurately quantify the *global* range of precipitation rates and types (rain, snow etc.). In turn, global observations of precipitation are most efficiently made from space. Great strides in the measurement of global tropical rainfall have occurred recently as a result of the NASA Tropical Rainfall Measurement Mission (TRMM). However, future international endeavors such as the Global Precipitation Mission (GPM) will require an expanded precipitation measurement capability due to the extension of the measurement to higher latitudes. Specifically, the NASA Precipitation Measurement Mission (PMM) and GPM algorithm development and Ground Validation (GV) teams are in great need of GPM pre-launch data sets for developing space-based snowfall detection and estimation algorithms. These data sets are needed to (1) develop and validate physical models that convert the physical characteristics of single snowflakes (shape, size distribution, density, ice-air-water ratio) to their radiative properties (asymmetry factor, absorption, scattering, and backscattering coefficients); and (2) relate the bulk layer radiative properties to calculated and observed passive microwave radiances and radar reflectivities.

Implicit to items (1) and (2) is the ability to effectively observe and quantify the characteristics of falling snow (rate, density, particle habit etc.) over domains the size of at least a single satellite and/or radar-pixel O[10-100 km^2]. However, a cost-effective and optimal set of methodologies to perform these measurements, indeed, even a determination of what measurements are most relevant has yet to be developed. Accordingly, during the winter of 2006-2007 a subset of the GPM/PMM science team participated in the Canadian CloudSat/Calipso Validation Project (C3VP; Hudak et al., 2006a,b). C3VP was a multi-national, multi-agency field experiment hosted by Environment Canada (EC) and centered on the Centre of Atmospheric Research Experiments (CARE) site, located near Egbert, Ontario, Canada (Fig. 1).

Figure 1. Location of C3VP CARE site (red dot) in Ontario, Canada.

GPM/PMM scientific objectives for C3VP included:

a) Collection of measurements enabling development of models that convert microphysical properties of snow to observed radiative properties (i.e., GPM dual-frequency radar reflectivity, passive microwave imager radiances);
b) Support of cloud resolving model (CRM) microphysics validation for simulations of lake effect and synoptic snowfall events in support of retrieval algorithm testing and development;
c) Testing of prototypes and further assessment of GPM GV ground-based instrumentation needs *and* methods for measuring snowfall and validating spaceborne snowfall measurements.
d) Collection of datasets supporting development of satellite simulator models (e.g., coupled CRM, Land-Surface, and radiative transfer models).

Herein we present an overview of C3VP as related to GPM/PMM, including a few preliminary results.

2. C3VP EXPERIMENT DESIGN AND NASA GPM/PMM INSTRUMENTATION

The C3VP field campaign was organized around four intensive aircraft observation periods (IOPs). Each IOP

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was conducted for a duration of ~10 days. In turn the IOPs were embedded within an extended period of continuous surface-based observations collected from October 2006 – April 2007.

Operations during IOPs were organized around three specific scientific thrusts. The first and primary emphasis of C3VP consisted of GV activities related to CloudSat/Calipso (CC) science and algorithm retrieval validation. The second component (Cloud-Layer Experiment-10; CLEX-10) involved process studies of mixed-phase non-precipitating mid-level layered clouds (cf. Carey et al., 2007, this conference). Both the CC and CLEX components of C3VP focused heavily on cloud particle measurements (ice and mixed phase) via ground (CARE site) and airborne radar and cloud microphysical measurements (Table 1).

Table 1. C3VP CARE Instrumentation

Organization/Instrument	Air/Ground
NRC Convair-580 (State parms, full suite of 2-D, 1-D microphysics, W/Ka band radars, G-band radiometer)	Air
NASA JPL W-band radar	Ground
King City C-band dual-pol radar (WKR)	Ground
McGill U. Verti-X, X-band Doppler radar	Ground
EC 915 MHz Wind Profiler	Ground
Prof. Radiometer (23, 30, 51-59 GHz)	Ground
NASA GRC Radiometer (89, 150 GHz)	Ground
EC Surface Met. Stations	Ground
EC Ceilometer	Ground
EC Rawinsonde	Ground
EC POSS Radar	Ground
EC/DRI Hot Plate	Ground
McGill U. HVSD (Hydrometeor/Velocity Shape Detector)	Ground
EC/Penn. St. suite of IR radiometers	Ground
EC FD12P Visibility meter	Ground
EC Snow and Precip. Gauges (DFIR, NIPHER, Geonor, pit gauge etc.).	Ground
McGill U. Ground Precip. Photography	Ground

Table 2. C3VP CARE GPM/PMM Instruments

Organization/Instrument	Air/Ground
U. Mass. AMFR (Ka/Ku/W Radar)	Ground
CSU 2D Video Disdrometer	Ground
NASA WFF Parsivel Disdrometers (2)	Ground
NASA WFF Snow Video Imager	Ground

The third component of C3VP was the NASA GPM/PMM GV snowfall measurement component. For this effort NASA-GPM/PMM augmented C3VP instrumentation shown in Table 1 with the UMASS Advanced Multi-Frequency Radar (Ka, Ku, W bands; first ever field deployment), the Colorado State University 2D Video Disdrometer (2DVD), two NASA Parsivel disdrometers, and the NASA snow video imager (SVI) [Table 2].

Particular emphasis on intensive radar sampling of snow by scanning multi-frequency radars (e.g., AMFR) was accomplished during the third IOP (January 8-28, 2007). During IOP3 GPM/PMM requested specific flight patterns to be flown over/near the CARE site (Figs. 2a-b) within range of the AMFR radar (~20 km). Concomitantly, the King City radar (WKR) conducted RHI scans every 10-20 minutes that were oriented over the CARE site and AMFR radar, (331°) and through the flight pattern (when applicable). Spiral descents were centered just upstream of CARE (Fig. 2b), which was located on the downwind edge of the spiral. When there were no flight operations, WKR multi-parameter RHI scans were collected over the CARE site during precipitation (occasional time-series data collection at several fixed elevation angles was also collected at WKR). It is important to note that *the WKR radar is* currently *used as an operational platform in the EC national radar network*; however upon completion of its mandatory 10-minute operational scan cycle it retains the flexibility to conduct several minutes of research scanning- a true benefit to field studies such as C3VP.

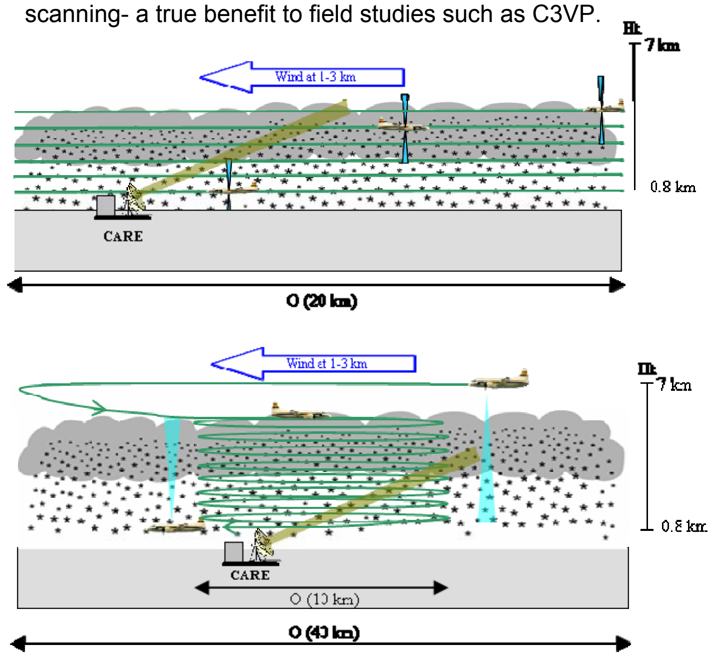

Figure 2. Basic Convair 580 flight patterns flown during GPM/PMM precipitation sampling. a) top, stacked straight legs; flown in lake-effect bands and synoptic event; b) bottom, spiral descent, flown in synoptic event.

Collectively, numerous snow events including both synoptic and lake effect snow bands were sampled in a coordinated fashion by C3VP airborne and ground-based instrumentation. These cases will provide the backbone of detailed microphysical and radiative transfer analyses. The longer duration extended dataset consisting of gauge and disdrometer measurements of snowfall over the winter will also be used in the near term to determine occurrence and threshold statistics for high frequency (e.g., ≥ 85 GHz) passive microwave detection of snowfall over land via the coincident AMSU-B and MHS overpasses on NOAA polar orbiting satellites (i.e., proxies for future GPM GMI frequencies).

With regard to more coordinated and detailed precipitation microphysical analyses (e.g., Sec. 3), initial disdrometer and radar analysis efforts focused on a snow event from December 6, 2006 (cf. Tokay et al., 2007, this conference). However, more recent efforts have shifted focus to an IOP3 priority case-period that included contrasting lake effect and synoptic scale snow events (20-22 January, 2007). For these events robust coordinated sampling occurred between aircraft and ground-based multi-frequency scanning polarimetric and vertically pointing radars, and the disdrometer/gauge infrastructure located at CARE (Tables 1-2). We now present examples of analysis from the 22 January 2007 synoptic event , and from the early 6 December 2006 event.

3. THE 22 JANUARY SYNOPTIC SNOW EVENT

An upper level short-wave at 500 mb accompanied by a surface low past across the area and to the northeast of CARE between 0000 UTC and 1200 UTC on January 22nd. Accompanying this storm system was a wide spread area of light to moderate snow that peaked in intensity over the CARE site between 0200 and 0800 UTC (Fig. 3).

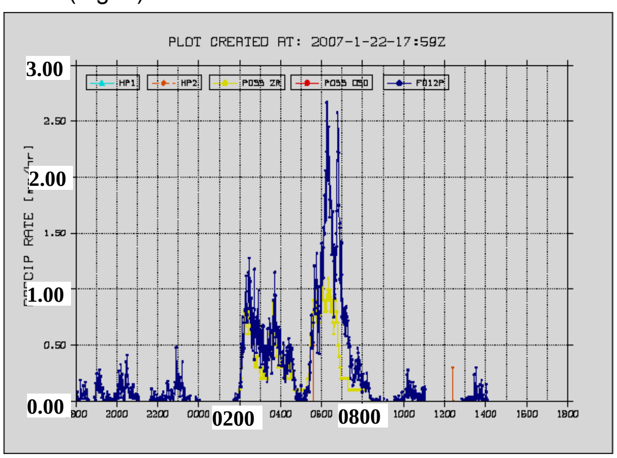

Figure 3. Time series of precipitation rate (water equivalent) from several gauges and POSS' instruments at the CARE site.

Surface temperatures during this event were relatively cold, -9ºC to -10ºC and radiosonde data collected during the event indicated near water-saturated conditions (and definitely ice supersaturated conditions) in the first several km of the sounding. Winds were generally moderate at surface, on of order 5 m s^{-1}, for the duration of the event.

3.1 Radar Observations

Figures 4a-b show examples of WKR radar reflectivity (Z) and differential reflectivity (ZDR) collected at an elevation angle of 0.8º (~550 m above CARE). These PPIs were collected just after the C580 aircraft completed a spiral descent over the CARE site and was in the process of performing a stepped leg pattern oriented along a 331º azimuth from the WKR radar, just to the northwest of the CARE. Snowfall at this time was broad in area coverage and slightly heavier just to the east and southeast of the CARE site (Z of 20-25 dBZ). ZDRs at this elevation generally exhibited slightly positive values of ~0-0.5 dB. WKR RHI scans taken over the CARE site are shown in Figs. 5a-b. The combined polarimetric data indicate that the snowfall evolved as smaller ice particles and snow in layers aloft (some of it in horizontally oriented bands near 2km; Fig 5b) that grew rapidly and subsequently aggregated while descending into the lowest 2 km of the troposphere. Not coincidentally, the lowest 2 km of the troposphere is where radiosonde data suggest that the troposphere was ice supersaturated. Coincident observations of snow habits at the ground indicated that the aggregates were composed of complex branched stellar and dendritic crystals (Fig. 6).

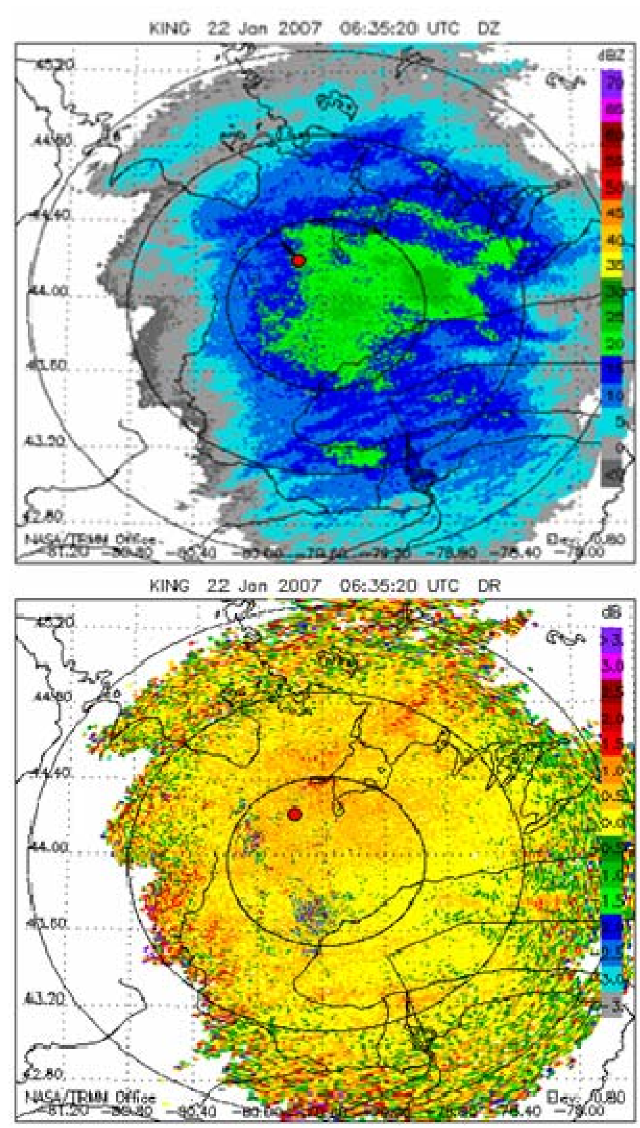

Figure 4. King City C-band radar a) top, Z; and b) bottom, ZDR, taken at 05:20:44 UTC and at an elevation angle of 0.8º. Approximate location of the CARE site indicated by red dot.

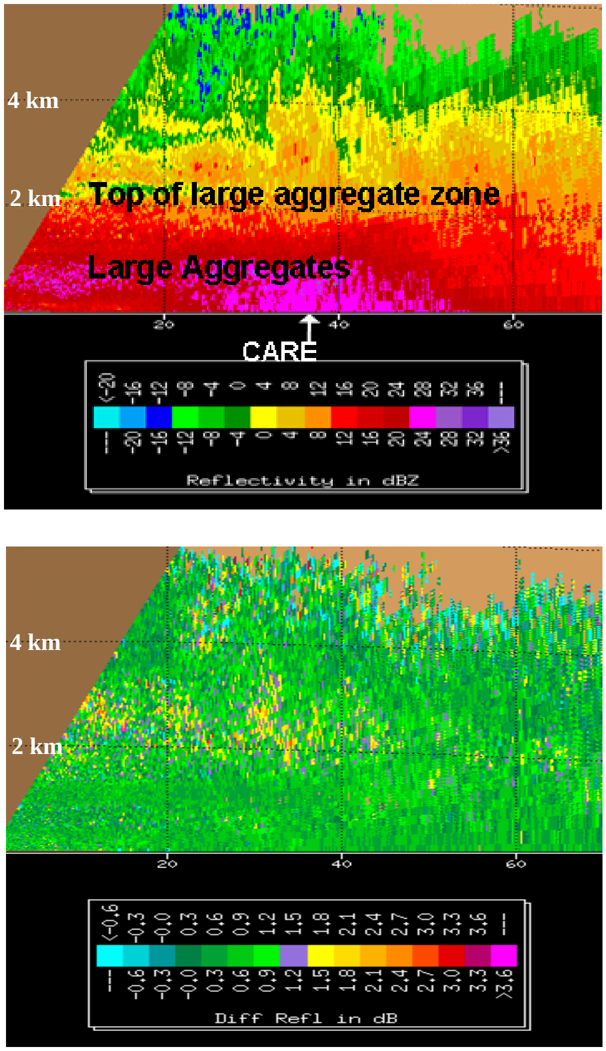

Figure 5. WKR RHI scans 01/22/07 0624 UTC. a) reflectivity; b) bottom, ZDR. Location of CARE site is indicated in (a).

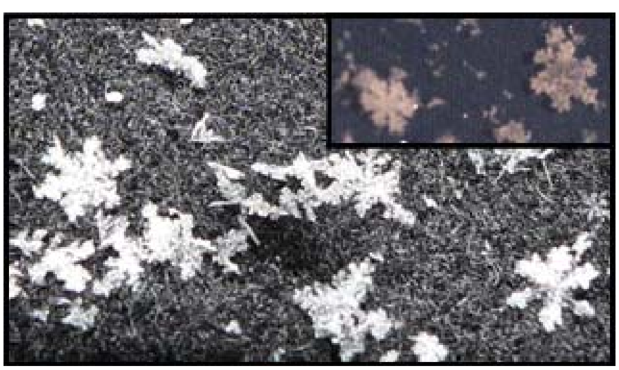

Figure 6. Zoomed digital camera images of snow observed at the ground during the 01/22/07 case (background is felt). Note presence of dendritic and branched stellar crystals.

In addition to the WKR radar cross sections, the UMASS AMFR collected steady RHIs, low-level sector PPIs, and one multi-angle time series volume during the entire event. Figure 7 shows an example of the higher spatial resolution of the Ku-frequency of the AMFR radar. Note that the values shown are *not* calibrated and should only be interpreted as relative values of reflectivity. Even still, the AMFR radar return illustrates the presence of upper level fall streaks and horizontal banding at low levels associated with the snowfall evolution. After post-processing of the data (now underway at CSU and UMASS), it is anticipated that the AMFR will provide robust, high resolution dual-frequency ratio and polarimetric information for retrieval of ice particle and snowfall characteristics.

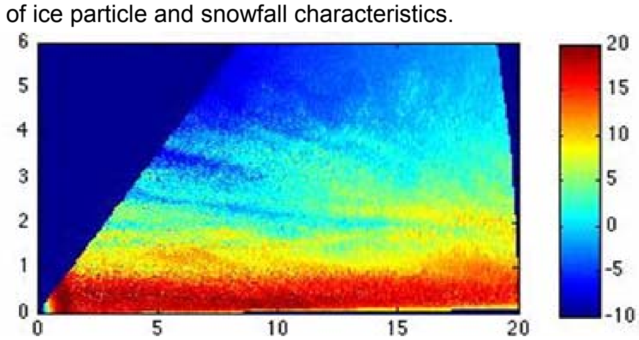

Figure 7. Example RHI cross section from the AMFR radar at Ku-band. Note that for the purposes of display the units here are plotted in the form of an uncalibrated, relative returned power.

3.2 Example aircraft observations

As noted above, the C580 aircraft flew a descending spiral pattern (~10 km in diameter) over and to the northwest of the CARE site. The spiral commenced near 0600 UTC at an altitude of 7 km and was completed near 0627 UTC at an altitude of ~600 m AGL. During the descent little if any cloud water was encountered by the C580. In contrast, this was not the case on January 20th during the lake effect case where the depth of the cloud bands was typically quite shallow (e.g., 2 - 3 km), but snow much heavier, and cloud water contents up to ~0.5 g m^{-3} were detected.

Figure 8 presents an example of the particle types observed by the 2D-P probe during the spiral descent between altitudes of 2 and 3 km (transition to the larger aggregate zone discussed in Sec. 3.2). Of particular note is the rapid transition that occurs to much larger aggregated snowflakes between the 2.5 and 1.5-2 km levels. This transition in particle size seems to be consistent with the changes noted early in the cross-sections of radar data (Figs. 5a-b).

3.3 Disdrometer observations and retrievals

Of particular interest to ground validation activities for C3VP, and relative to GPM/PMM, were multi/redundant instrument observations/measurements of the snow particle size spectra, snow fall rates and melt water equivalents (MWE), and retrievals of bulk snow density-especially the parameters used in functional forms of inverse diameter-density relationships (e.g., $\rho = \alpha D_c^{\beta}$, where "c" is a measure of characteristic diameter such as median volume diameter, D_0; Brandes et al., 2007).

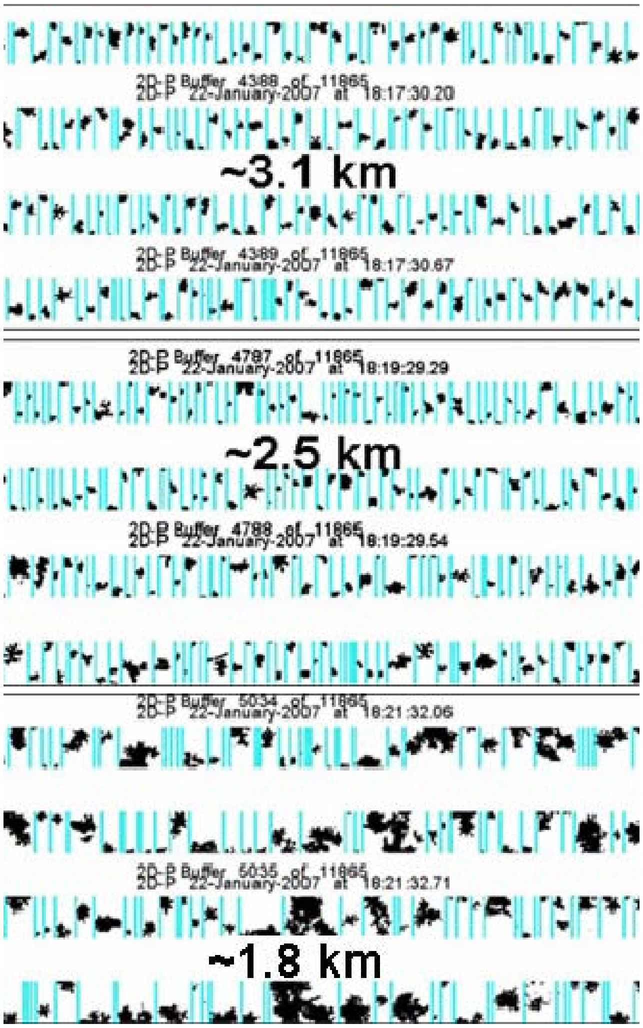

Figure 8. C580 2D-P data from approximately the 3.1 to 1.8 km levels during the spiral descent over CARE. Note that indicated times in the data are offset by 12-hours (e.g., the time at 3.1 km is actually 06:17:30 UTC etc.). The largest particles are ~1.5 cm in their longest dimension.

These observations facilitate a) further development and improvement of solid hydrometeor radiative transfer models- work required to advance physically-based snowfall retrieval algorithms; b) further testing, improvement, and mapping of ground-based "point" - diagnosed bulk particle characteristics to much larger volumetric sampling domains intrinsic to radar measurements; and c) a determination of which instruments and techniques can best serve the needs of satellite ground validation in snowfall regimes.

First we consider direct comparisons of snow size spectra measured by the 2DVD and the Parsivel disdrometers for the 0200-0300 UTC time period on 22 January (Fig. 9). First note that the two collocated Parsivel instruments yielded very similar size distributions for the same time period (Fig. 9a). This is reassuring. However, comparing the estimates of particle size distribution between the Parsivels (Fig. 9a) and the 2DVD (Fig. 9b) for this case, it is clear that there is a large discrepancy in retrieved number concentrations between the two instruments. This is especially acute for particle diameters < 4-5 mm (cf. Tokay et al., 2007), where the Parsivel concentrations are a factor of 10 larger than the 2DVD. In post-analysis, it has been determined that a camera mismatch in the 2DVD (front and side views) caused this discrepancy- hence the 2DVD data are currently being corrected to account for this error.

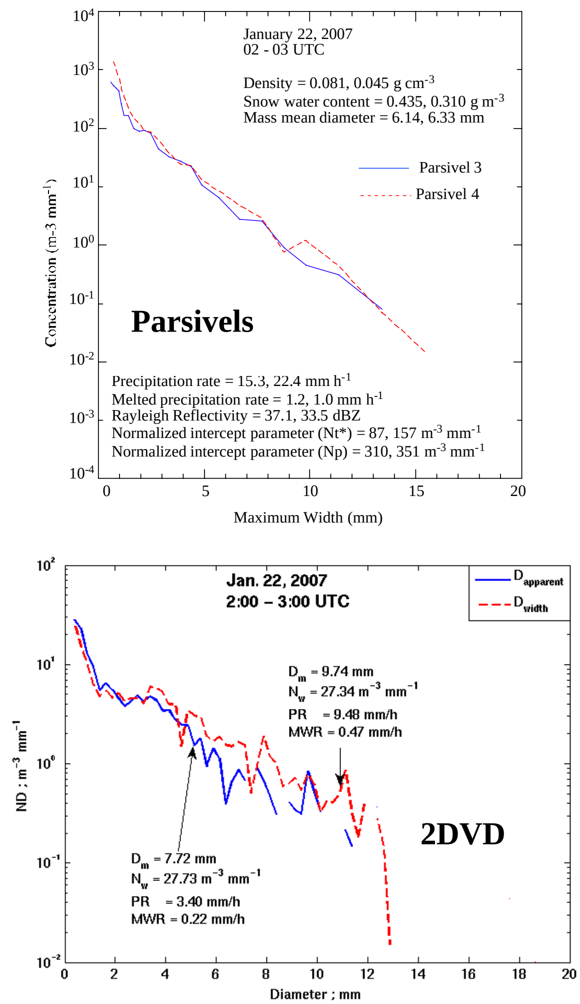

Figure 9. Particle size distributions for (a), top, the two NASA Parsivel disdrometers; and (b), bottom, the 2DVD using two different metrics of particle diameter (apparent diameter and the averaged maximum widths observed for the two 2DVD cameras- similar to the measurement made by Parsivels).

For further intercomparison calculations of MWE were performed using the POSS, 2DVD and FD12P sensors. The POSS estimate was 3.4 mm and the FD12P estimate was 4 mm. The 2DVD MWE estimate was lower at 2.2 mm. Though not collocated with the aforementioned triplet of measurements, the DFIR gauge (~100 m from the POSS, 2DVD and FD12P) measurement of MWE was 2.4 mm. Note that the POSS and FD12P methods for observing and computing MWE are different, but they both arrived at similar and higher MWE values than the 2DVD. It is currently hypothesized that lower value of MWE estimated by the 2DVD is due to the camera mismatch problem.

Most importantly *this case clearly illustrates why multiple measurements of the same parameter(s) combined with other constraints can be useful to ground validation*- i.e., clear discrepancies between the measurements motivate analysis and correction of instrument error, and improve validation measurements.

4. DECEMBER 6, 2006: EXAMPLE OF GROUND PLATFORM CONSISTENCY

Here we provide an example of instrument consistency for a snowfall event that occurred on 6 December 2006 (no 2DVD camera mismatch). For this case agreement between the platforms was good as illustrated for the Parsivels and SVI in Figs. 10 a-b. Here, confidence in the size distribution measurements is high.

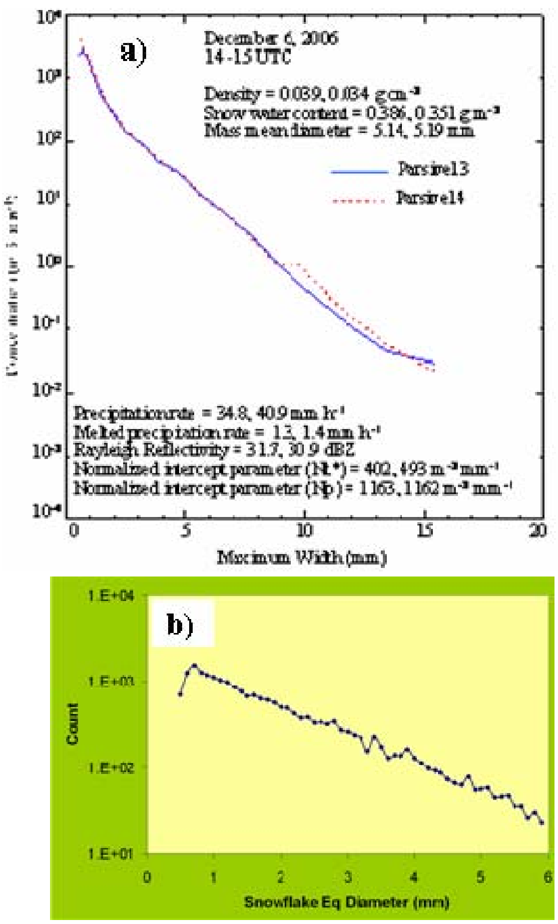

Figure 10. Particle size distributions for collocated (a) Parsivel disdrometers; and b) the snow video imager (truncated to a size of 6 mm). Note the favorable concentration comparison between the two instruments.

As a further example of the inter-platform consistency for this case, when the 2DVD measurements were processed to compute radar reflectivity and MWE (iteration of T-matrix simulations and a matching procedure that used the density-diameter relationship of Brandes et al. (2007) constrained by WKR radar reflectivity; cf. Tokay et al., 2007), it was found that *without any need to adjust the Brandes et al. coefficient in the density-diameter relationship*, the 2DVD, POSS and WKR reflectivities were all very well matched (Fig. 11). Note that in the case of 22 January, the α-coefficient in the Brandes et al. (2007) relationship required an unreasonably large adjustment (factor 2) to produce a 2DVD reflectivity that matched the WKR and POSS Z.

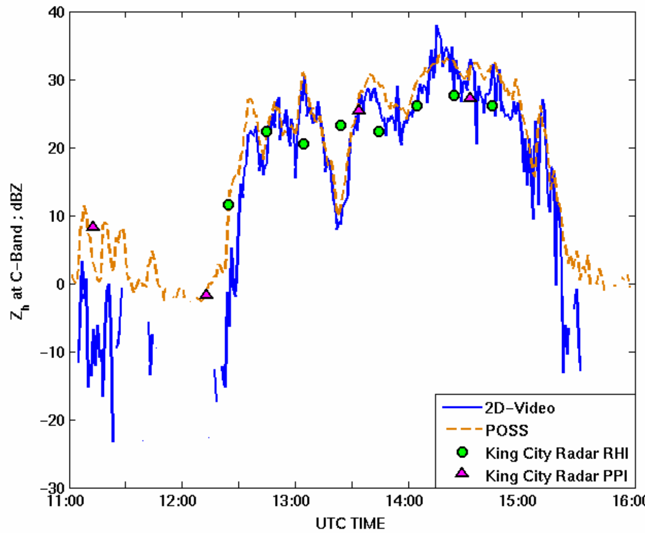

Figure 11. Time series of equivalent radar reflectivity factor for 6 December 2006 measured by the King City radar over CARE and as computed from the 2DVD and POSS. 2DVD data are averaged over a 3 minute period, POSS 1 minute.

5. SUMMARY AND CONCLUSIONS

This paper presented an overview of NASA GPM/PMM participation in the C3VP field campaign. In the broadest sense GPM/PMM leveraged its participation in C3VP to collect detailed measurements (airborne and ground-based) of snowfall characteristics in order to accommodate satellite retrieval algorithm development and validation for future satellite missions such as GPM. The snowfall retrieval algorithm problem is particularly pressing given the relative dearth of *reliable* physically-based high frequency (e.g. ≥85 GHz) passive microwave algorithms and a related set of unresolved questions that fundamentally relate to the development of these algorithms.

For example, consider Fig. 12a-b (22 January case). Here the snowfall rate at the ground (Fig. 3) differed by *at least* a factor of two during the two AMSU-B overpasses. However, the difference in brightness temperature between two 183 +/-7 GHz channels (the channel that exhibited *the most pronounced* brightness temperature depression of all the frequencies) was a relatively small value of only 6º–8º K. This raises the question of passive microwave high frequency channel sensitivity to snowfall rate (as opposed to snowfall occurrence or detection). Do the physics of snow influence this sensitivity? How does the background land-surface influence the sensitivity (e.g., emissivity)? Can we *accurately estimate and reliably detect* snowfall over land using passive microwave measurements? If so at what time and space scales? Relative to algorithms designed to make the spaceborne measurements, can coupled CRM/Land Surface Models provide the required fidelity to test and further develop radiometer and/or radar retrieval algorithms?

Implicit to the process of answering *all* of the above questions is the need for validating and/or reference ground measurements of snowfall rate and a plethora of particle physical characteristics. To address this need the NASA GPM/PMM ground validation community must formulate robust approaches and methodologies to validate satellite-based snowfall algorithms *well prior to GPM launch*. The C3VP field experiment, a prototype for future efforts, served these purposes well.

6. REFERENCES

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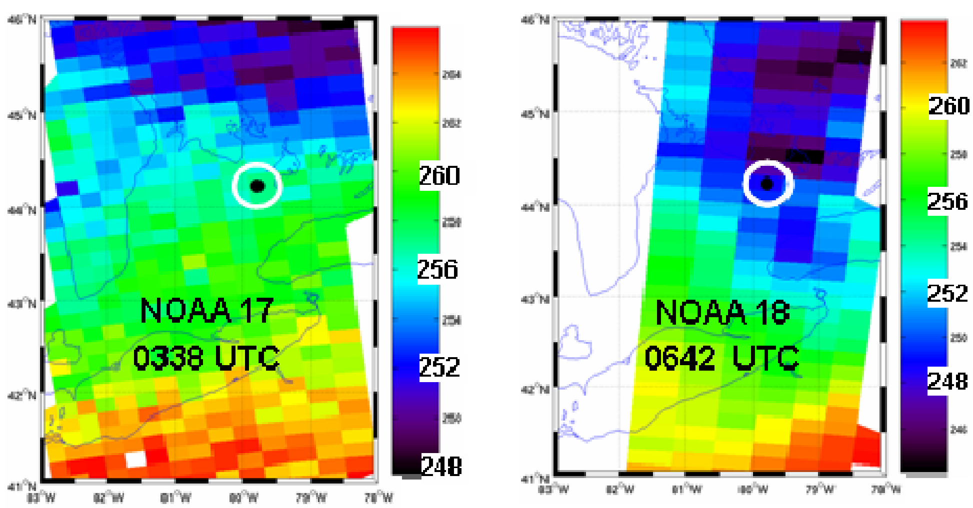

Figure 12. AMSU-B brightness temperatures for the 183 +/- 7 GHz channel at (a) 0338 UTC, left panel; and (b) 0642 UTC, right panel. Note color scales are slightly different for each panel. Compare to Figure 3 for snowfall rate over the CARE site (indicated by circled black dot).