P10.5 COLD RAIN EVENT ANALYSIS USING 2-D VIDEO DISDROMETER, C-BAND POLARIMETRIC RADAR, X-BAND VERTICALLY POINTING DOPPLER RADAR AND POSS

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1. INTRODUCTION

It has been shown in the recent past that the 2-D video disdrometer (2DVD) is capable of determining shapes and fall velocities of hydrometeors falling through its 10 cm by 10 cm sensor area (Thurai and Bringi, 2005; Thurai et al. 2007; Huang et al. 2007). It has also been used in an intercomparison study with a C-band polarimetric radar and a UHF wind profiler during a seasonal event in a sub-tropical climate (Bringi et al. 2006). Attenuation correction schemes were developed for the C-band polarimetric radar based on the data analysis of simultaneous 2DVD measurements (Thurai and Hanado, 2005).

In this study, we examine a mid-latitude cold rain event using a low-profile 2DVD (Randeu et al., 2002; Kruger and Krajewski, 2002), a C-band polarimetric radar (Hudak et al, 2006) and a vertically-pointing X-band Doppler radar (Zawadzki et al, 2001) as well as a precipitation occurrence sensor system (POSS; Sheppard, 1990). The mid-latitude region in this case is a well-instrumented site in Ontario (ON), belonging to Environment Canada, where the 2DVD was installed in November, 2006, and where the X-band radar and POSS were already present. On 2 consecutive days soon after the installation, a cold rain event passed over the 2DVD site. The C-band dual-polar operational weather radar situated in King City, ON, some 30 km away from the 2DVD site, was also used to observe and analyze this event.

This paper compares simultaneous observations from the four instruments and shows how their data could be utilized to (a) infer the rain microstructure and (b) assess various hydrometeor classification schemes that have been proposed in the recent past.

2. INSTRUMENTS USED AND DATA

The four instruments used in this study have been fully described in previous articles hence only the salient points will be given here. Table 1 summarizes the instrument locations and data.

Table 1: Summary of various instruments and data

Instrument (Reference)	**Location**	**Data**	**Events** **(1)** 30 Nov '06 (15:00 - 24:00) **(2)** 01 Dec '06 (04:00 -22:00)
2DVD (Randeu et al, 2002; Kruger and Krajewski, 2002)	**CARE site, ON	Shape, size & fall velocity of individual hydrometeors	Continuous observations
C-band King radar (Hudak et al 2006)	King City, ON	Z_h, Z_{dr}, Φ_{dp}, ρ_{co}	RHI scans over CARE site and PPI scans at low elevation, taken every 10 minutes
POSS (Sheppard 1990)	**CARE site, ON	DSD in rain derived from bistatic Doppler spectra and hydrometeor types	Continuous observations
VertiX (Zawadzki et al, 2001)	**CARE site, ON	Height profiles of Z, mean velocity and spread from Doppler power spectra	Continuous observations

(**CARE : Centre for Atmospheric Research Experiments)

The 2DVD provides images of individual particles using two fast line scan cameras, with orthogonal views, and separated by a precisely known distance. The configuration enables each particle to be contoured (Thurai et al. 2007, Huang et al. 2007) and its fall velocity determined. The C-band King City radar is an operational system and provides co-polar reflectivity (Z_h) for horizontal polarization, differential reflectivity (Z_{dr}), differential phase (Φ_{dp}) and the co-polar correlation coefficient (ρ_{co}) over 112 km maximum range with a range resolution of 125 m and antenna beamwidth of 0.6 deg. The vertically-pointing X-band radar (VertiX) is collocated with the 2DVD and measures the Doppler spectra over 10 km range, with a minimum range of typically 200 m and a range resolution of 37.5 m. The POSS (a small bistatic 10.5 GHz Doppler radar) is also collocated with the 2DVD

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and is capable of providing drop size distribution in rain and information on hydrometeor types derived from the bistatic Doppler spectra. Out of the four instruments, data from the 2DVD, the King City radar and the POSS are used quantitatively for rain microstructure measurements in this study whereas VertiX data are used to provide qualitative information on hydrometeor types and melting layer heights in stratiform rain..

Observations made over two consecutive days (30 November and 01 Dec 2006) are reported here. On the first day, the 2DVD data showed that it was almost all liquid water hydrometeors (i.e. rain) at ground level, confirmed further by VertiX measurements which showed a clear bright-band at around 2 km above ground level throughout the event. The second day was more of a transition event from largely stratiform rain to melting snow and eventually to dry snow. RHI and PPI scans from the King City radar taken at regular intervals were used to extract the Z_h, Z_{dr}, K_{dp} and the ρ_{co} data over the 2DVD/VertiX/POSS location.

3. COLD RAIN EVENT ON 30 NOV 2006

3.1 Observations

Vertix observations of the 30 Nov 2006 event are given in Fig. 1(a) & (b). The panel (a) shows the time variation of the X-band reflectivity as a function of height and panel (b) shows the Doppler mean velocity. The melting region is clearly seen in both cases, occurring at around 2.5 km height at the beginning of the event and reducing to 2 km at the end of the event. The lowering of the bright-band correlates well with the ground temperature recording (Fig. 1(c)) which shows a variation from 8 C at 15:30 down to around 5 C at 23:00. In the snow region above the bright-band, the relatively high Doppler mean velocity (> 2 m/s) at around 19:00 is indicative of the existence of high density snow particles due to riming process. This process is apparent only at certain times and, together with the gradual reduction of the bright-band height indicates that this event, even though stratiform in nature, has variable micro-physical processes involved throughout its duration (unlike steady state stratiform precipitation).

Fig. 2 shows the RHI scan taken at 19:02 over the CARE site. Of the four radar-measured parameters, ρ_{co} shows the bright-band most clearly, indicating both the upper and lower regions of the melting layer. In the snow region above and the rain region below has ρ_{co} almost equal to one but in the melting region itself, ρ_{co} is significantly less (< 0.95). Several other RHI examples (not shown here) have also shown this contrast and have indicated that of the four radar parameters, ρ_{co} is the most sensitive parameter to the melting region in stratiform precipitation. This high sensitivity is also useful for identifying rain-snow boundaries in winter precipitation, as was shown by Hudak et al (2006).

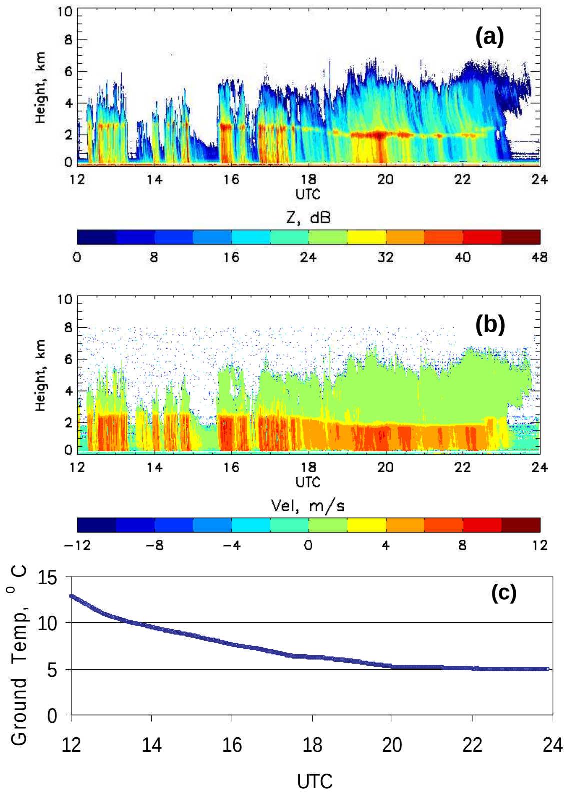

Fig. 1: Time series of Z - height profiles (top) and mean Doppler velocity – height profiles (middle) from the VertiX radar, and ground temperature recordings (bottom) at CARE site for the 30 Nov 2006 event.

3.2 Intercomparisons

Reflectivity comparisons at the CARE site between the four sets of data are shown as time series in Fig. 3a. The 2DVD data represent Z_h computed over 1-minute DSD, the POSS data are derived from the bistatic Doppler spectra sampled every minute, and the VertiX data were taken over a typical sampling time of 2 s, (prf of 650 Hz). All three are obtained from continuous observations. The 'discrete radar points' represent the reflectivity data extracted from both low elevation (0.2°)PPI scans as well as RHI scans over CARE site. The POSS and the 2DVD reflectivities are purely derived from the DSDs, whilst the VertiX radar needed their Z_h values adjusted in absolute terms in order to agree closely with the POSS and the 2DVD derived Z_h values. (There was no need to apply reflectivity calibration offsets to the King City radar). The agreement between all four datasets is remarkable, except for low reflectivity (< 10 dBZ) where it appears that POSS is relatively more sensitive than the other instruments.

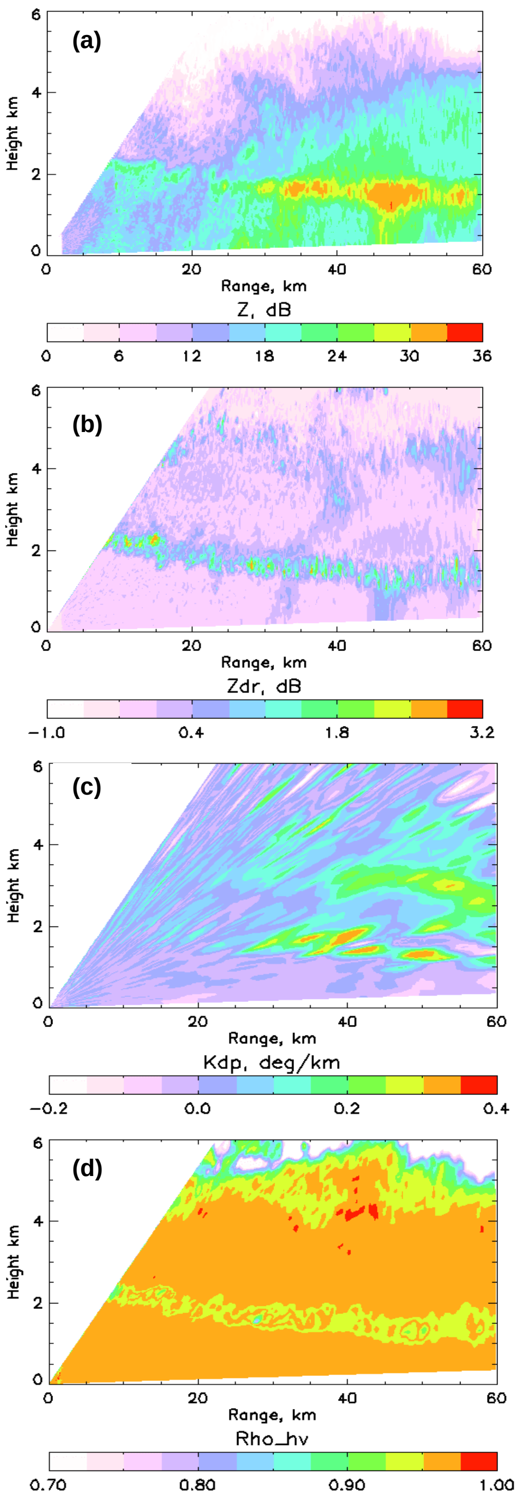

Fig. 2: RHI scan taken at 19:02 UTC on 30 Nov 2006, over CARE site (at around 30 km range). (a) Z_h, (b) Z_{dr}, (c) K_{dp} and (d) ρ_{co}. Of the four, ρ_{co} shows the upper and lower regions of the melting layer most clearly.

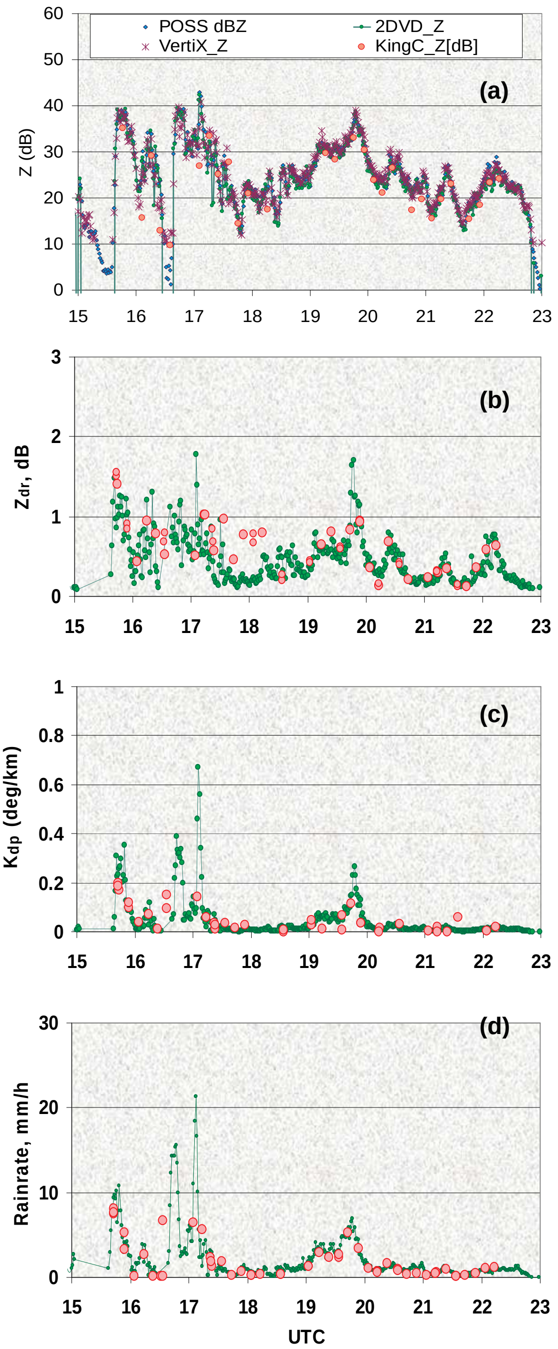

Fig. 3: Time series comparisons of (a) Z_h, (b) Z_{dr}, (c) K_{dp} and (d) rainfall rates from the 2DVD (green line), King City radar (orange points), POSS (blue dots) and VertiX radar (purple stars) over CARE site on 30 Nov 2006. The polarimetric parameters (b) and (c) are compared between the C-band radar and the 2DVD. For rainfall rates, the C-band K_{dp} based estimates are compared against the 2DVD estimates based on 1-minute integrated DSD's. (These comparisons are done in a similar way to those given in Bringi et al., 2006, for the Okinawa, sub-tropical site).

The 2DVD data also enable the polarimetric parameters Z_{dr} and K_{dp} (specific differential phase) to be determined, since it records the shape, size and orientation of each hydrometeor. The calculations, shown in Fig. 3(b) and 3(c) and compared with the C-band measurements, assume the smoothed conical fitted equation given in Thurai et al (2007) for the mean shapes and a Gaussian distribution for the drop canting angle with 0º mean and 5º standard deviation. Apart from Z_{dr} at around 18:00 (corresponding to relatively low Z_h values of around 15 dBZ), the agreement is generally close, i.e. within 0.2 dB. The K_{dp} comparisons also show reasonable agreement. Note, (i) the derivation of K_{dp} is based on iterative Φ_{dp} filtering (as in Hubbert and Bringi, 1995) and, (ii) the 2DVD based calculations are sensitive to the assumed drop shapes. Fig. 3(d) compares the K_{dp} based rain-rate estimates (from the C-band radar) and the 2DVD based rain rates derived from 1-minute integrated DSDs.

Further confirmation of mean drop shapes for this event can be seen in Fig. 4 which compares the Z_h - Z_{dr} variation in rain region from the King City radar and those computed from the 2DVD data over the entire period of this event. The latter superimposes well with the color intensity plot representing the variation derived from the C-band radar. The 2DVD computations are sensitive to the assumed mean drop shapes and any deviation from the most probable shapes would have given rise to noticeable disagreement between the color intensity variation and the black points in Fig. 4.

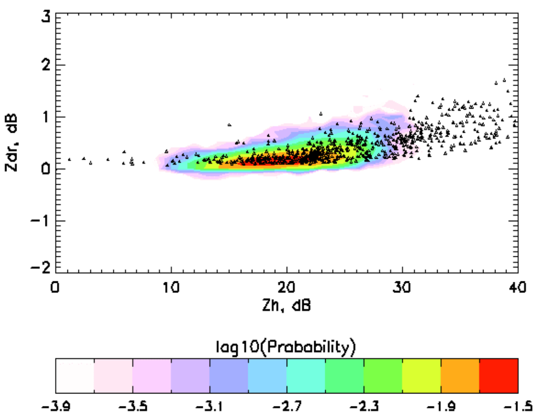

Fig. 4: Z_h - Z_{dr} variation in rain region from the King City radar data (color intensity plot) compared with the 2DVD data based estimates superimposed as black marks, for the 30 Nov 2006 event. The agreement gives independent confirmation for the most probable drop shapes in rain. The Z_h - Z_{dr} variation from the C-band radar also enables 2-dimensional membership functions for rain to be derived for hydrometeor classification schemes, the derivation being based on observations and not theoretical calculations.

3.3 *DSD comparisons*

POSS derived DSDs for the 30 Nov 2006 rain event show that the drops were mostly smaller than 3 mm, as shown in Fig. 5(a). This was also confirmed by the 2DVD data. The median volume diameter (D_0) values derived form POSS are compared in Fig. 5(b) with those derived from the 2DVD DSDs integrated over 1-minute. The agreement is excellent throughout the event. The estimated rainfall rates (Fig. 5(c)) also show close agreement, and hence imply that there is consistency between the DSDs measured by 2DVD and those inferred from POSS. Fig. 5(d) and 5(e) show two examples of DSD comparisons to illustrate the agreement. They represent rainfall rates in the 5-10 mm/h range and D_0's of 1.5-1.8 mm range.

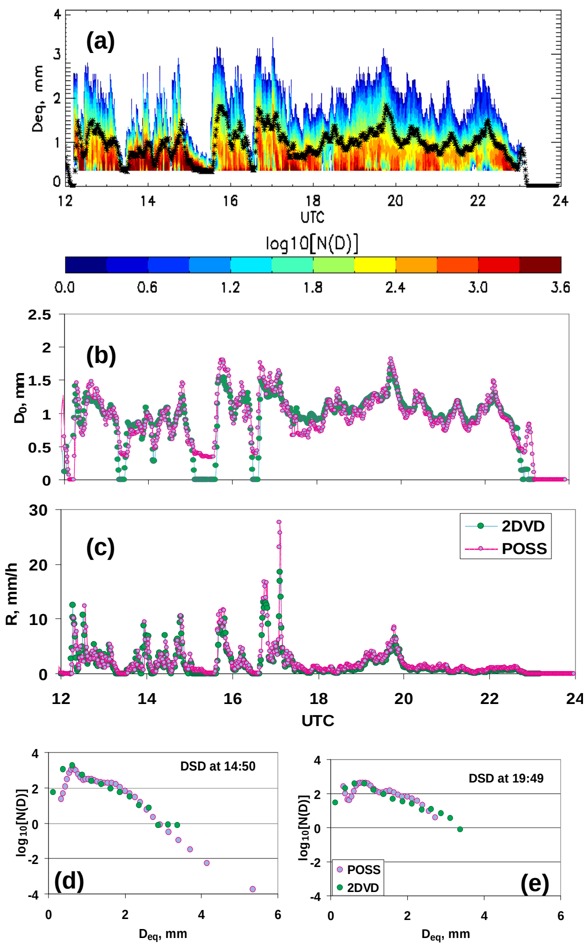

Fig. 5: DSDs for the 30 Nov 2006 rain event. (a) DSD time series from POSS, together with the D_0 values superimposed as black stars; (b) D_0 comparisons between POSS and 2DVD; (c) rainrate comparisons between POSS and 2DVD; (d) & (e) DSD comparisons at 14:50 and 19:49. Close agreement between POSS and 2DVD DSDs are seen for this (relatively low D_0) event.

4. TRANSITION EVENT ON 01 DEC 2006

Unlike 30 Nov 2006, the following day was more of a mixed phase hydrometeor event. The fall velocities from the 2DVD are shown for three different time periods in Fig. 6(a), (b) and (c). For comparison, the fall velocities for the rain event on 30 Nov is shown in Fig. 6(d). In all cases, the Gunn-Kinzer (G-K) curve is drawn as reference.

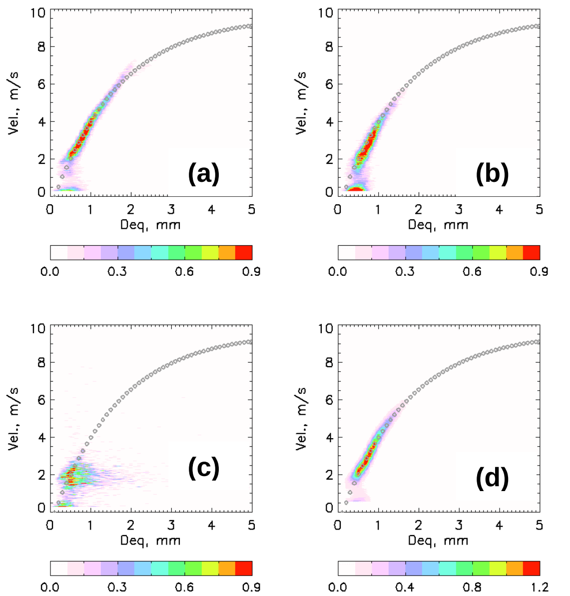

Fig. 6: Velocity-diameter variations from 2DVD for the time periods (a) 08:00 – 12:00, (b) 16:00 – 20:00, (c) 20:00 - 24:00 on 01 Dec 2006 and (d) for the entire event on 30 Nov 2006. Color scale represents $\log_{10}$ of the number of hydrometeors for a given D_{eq} and a given vertical velocity

Whereas the 30 Nov case shows near-perfect agreement with the G-K curve, the 1 Dec data deviate from it in different ways at different time periods. In Fig. 6(a) the small deviation in velocity (~ 0.5 m/s) above the G-K curve in the 1.5 to 2 mm diameter range suggests either rain mixed with a few ice pellets (or graupel or similar) or downdraft. . However, the axis ratio measurements taken during this time indicate the hydrometeors to be almost all rain. During the 16:00-20:00 UTC period, the fall velocities lie largely below the G-K curve, which indicates rain mixed with melting snow. Indeed the ground temperature at around 18:00 was recorded to be just below 2 ºC. After 20:00, the fall velocities indicate mostly dry snow.

Although Fig. 6(a), (b) and (c) are rigidly separated in time, the hydrometeor phase transition of course occurs more gradually. The VertiX radar bright-band (Fig. 7(a)) shows a gradual decrease in height, reaching ground level just after 20:00. This decrease in the melting layer height is also visible in the Doppler mean of the VertiX radar data (Fig. 7(b).

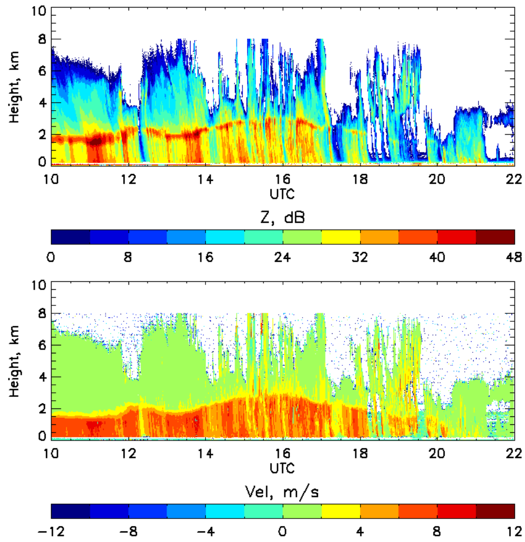

Fig. 7: Time series of Z - height profiles (upper panel) and mean Doppler velocity – height profiles (lower panel) from the VertiX radar at CARE site for the 1 Dec 2006 event. The bright-band reaches ground level soon after 18:00 UTC. This is consistent with the 2DVD fall velocity data shown in Fig. 6(a), (b) and (c).

The King-radar data extracted at and around the CARE site region are plotted as time series in Fig. 8. (The vertical spread of points for a given time represent the radar measured quantities extracted from individual 'pixels' at and around the CARE site over an area of 3 km by 3 km.)

Two significant features are worth noting, in terms of ρ_{co} :- (i) between 13:00 and 17:00, it remains steadily close to 1, and (ii) significantly lower values can be observed at around 11:00 as well as 21:00. From the 2DVD fall velocity data, case (i) can be attributed generally to rain whereas case (ii) arises due to two different hydrometeor conditions during the two time periods (near 11:00 and 21:00). The VertiX data at around 21:00 clearly shows the bright-band reaching ground level; hence the reduced ρ_{co}, together with (relatively) high Z_h, high Z_{dr} and high K_{dp} can be attributed to the melting layer or wet snow. For the 11:00 case, the VertiX data shows the bright-band to be higher than 1.5 km and the fall velocities from the 2DVD data indicate the hydrometeors at ground level to be mostly rain with broad drop size distribution and relatively high mass weighted mean diameter, D_m. The variation of D_m together with the width of the DSD derived from the 2DVD data are shown in Fig. 8(e), below the King City radar data. The reduction in ρ_{co} occurs at the time of high D_m (~ 2.6 mm) and large width (~1.4 mm). (Note the width here refers to the standard deviation of the mass spectrum as defined by Ulbrich and Atlas, 1998, and denoted by σ_m in Fig. 8(e)). The reduction in ρ_{co} can be attributed to the variance contribution due to drop oscillations together with the contribution from the size distribution (assuming they are uncorrelated, as in Bringi and Chandrasekar, 2001, equation 7.47). Indeed, our T-matrix calculations using the 2DVD based drop axis ratios and drop size distributions indicate that the magnitude of ρ_{co} at C-band could be used to estimate the width of the DSD in heavy rainfall. Fig. 9 is one such example, which shows the ρ_{co} versus σ variation for another rain event at the CARE site.

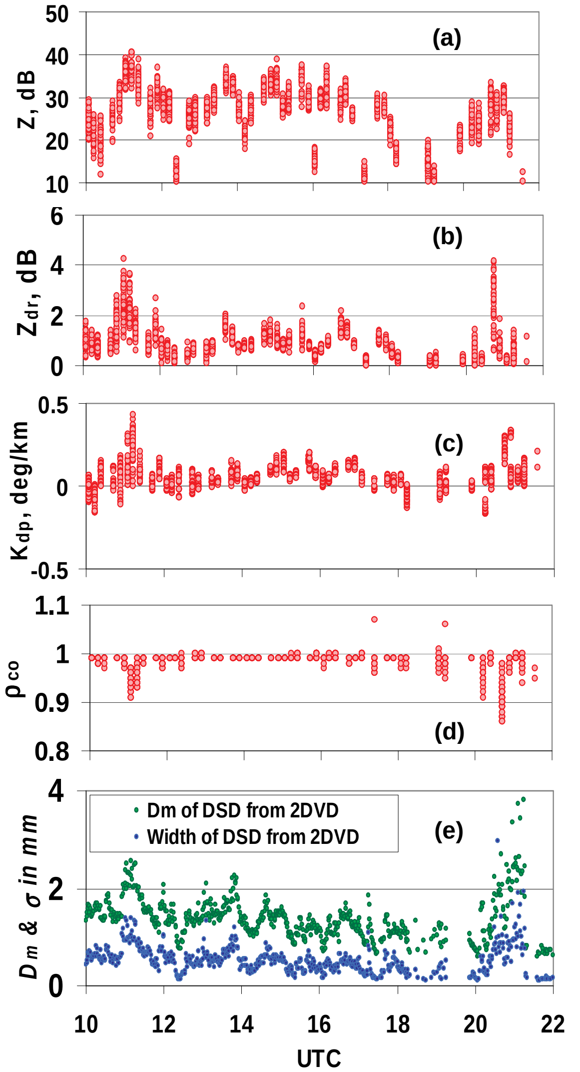

Fig. 8: Time series variation of (a) Z_h, (b) Z_{dr}, (c) K_{dp} and (d) ρ_{co} extracted from the King City radar data over CARE site for the 1 Dec 2006 event. Transition to melting snow occurs just after 20:00, indicated by the high Z_h, hign Z_{dr} and low ρ_{co}. The reduction in ρ_{co} seen at around 11:00 (during the rain period) corresponds to high D_m (~2.6 mm) and large width (~1.4 mm) of DSD derived from the 2DVD data, both shown in (e).

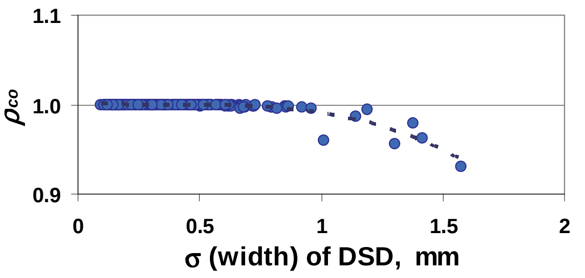

Fig. 9: Calculations using the DSD and axis ratios measured by the 2DVD for an event at the CARE site (27 April 2007), showing that ρ_{co} at C-band could be used to estimate the width of the DSD in heavy rainfall.

5. SUMMARY

Event analysis using the 2DVD data as well as the King radar, the VertiX and the POSS data for the 30 Nov 2006 and 01 Dec 2006 has highlighted several points, as follows:

For the 30 Nov 2006 stratiform event:

- Excellent agreement is seen between the 1-minute integrated DSD from the 2DVD and the POSS data throughout the event.

- Excellent agreement is seen in reflectivity throughout the event, amongst the four instruments used in this study, namely (a) 2DVD, (2) King radar, (3) POSS and (4) VertiX. This is despite the vast differences in (a) measurement principle, (b) sampling volumes, and (c) space/time averaging.

- K_{dp} derived from the 2DVD based DSD and axis ratio distributions agree well with the K_{dp}'s derived from the King radar data over the CARE site; so do the rainfall rates. This implies that the mean shapes have been accurately characterized.

- Z_h - Z_{dr} variation derived from the 2DVD data superimposes well on the corresponding intensity variation derived in the rain region from the King City radar data. The variation will be useful for deriving 2-D membership functions for hydro-class schemes. Similar membership functions can also be derived for the dry snow and wet snow regions

- ρ_{co} is very sensitive to wet snow; in fact it is the most useful radar parameter at C-band to detect the upper and the lower regions of the melting layer in stratiform precipitation; it can also be utilized to detect the occurrence of rain-snow boundary in winter precipitation.

For the 01 Dec 2006 transition event:

- Fall velocities from the 2DVD indicate mostly rain prior to 16:00, followed by the transition to melting (wet) snow at around 20:00 and subsequently dry snow after that. Enhancements in Z_h and Z_{dr} and a reduction in ρ_{co} occur during the transition from rain to melting snow. This transition is confirmed independently by VertiX Doppler measurements.

- D_m values of ~2.5 mm obtained from the 2DVD data during the rain period correspond to reduced ρ_{co} values of around 0.9 - 0.93 from the King City C-band radar. Lower and more typical values D_m (1-2 mm) give ρ_{co}'s which are close to 1. Moreover, T-matrix calculations using 2DVD data from other events have indicated that ρ_{co} at C-band could be used to estimate the width of the DSD for high rainrates.

- The combined datasets from the four instruments provide the means to develop and/or assess hydro-class schemes (e.g. Keenan et al, 2002) based on high-quality measurements. The King City radar with its narrow beamwidth (0.6°) at C-band is particularly valuable in achieving very high quality polarimetric data, especially ρ_{co}.

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