1. Introduction

The Great lakes region of Canada experiences significant winter snowfall events, including large scale synoptic systems, localized lake effect systems and a combination of both. Dual polarimetric radar observations of winter precipitation provides insights into the microphysical properties of the snowfall. The goal of this study is to describe the snowfall events in terms of the polarimetric variables, radar reflectivity $Z$, differential reflectivity $Z_{DR}$, cross-correlation coefficient $\rho_{HV}$ and specific differential phase $K_{DP}$.

In the region, lake effect band organization is related to the wind speed and direction, vertical wind shear, shape of the lake, and the temperature difference between the 850mb pressure level and the surface. Several studies have investigated the dynamics of these events (e.g. Barthold and Kristovich 2011; Niziol et. al., 1995). Long lake-axis-parallel snow bands over the south shore of Lake Ontario and Lake Erie have been investigated by dual-polarized X-band observations in relation to vortices and convection within these snow bands (Cermak et. al., 2012). In a concurrent study Ahasic et. al. (2012) attempted to relate the X-band radar observations with precipitation types and intensities recorded at the surface. A description of the synoptic-scale environment and interaction with the lakes in producing heavy snowfalls can be found in Liu and Moore (2004).

The King City C-Band dual polarized radar provided low elevation PPI scans every 10 minutes of $Z$, $Z_{DR}$, $\rho_{HV}$ and $K_{DP}$ at 0.25km range and 0.5$^\circ$ azimuthal resolutions for the study. Ground instrumentation available at the Center for Atmospheric Research (CARE), near Egbert, Ontario (http://pmm.nasa.gov/GCPEx) provided meteorological observations and precipitation data. The site is at 34km and 331$^\circ$ azimuth from the radar. In this study, precipitation rates and types from the Precipitation Occurrence Sensor System (POSS) (Sheppard and Joe, 2007), were used to relate the radar measurements with the variation of precipitation rates and particle types in the presented events.

2. Polarimetric properties of snow events.

Events were selected from the winter seasons from the years 2006 to 2012. The snow events in the region were classed into the three groups; lake effect squalls off Lake Huron and Georgian Bay, lake effect squalls off Lake Ontario, and large scale synoptic snow over the region. The orientation of lake effect squalls are determined by the wind direction and precipitation at the surface is highly localised, depending on location and distance from the core of the band. The synoptic snow systems produces widespread snowfall and often showed enhanced snowfall in embedded precipitation cores as the systems tracks across the area. A description of the dual polarization measurements illustrated by an example is presented for each category.

2.1) Lake effect off Georgian Bay and Lake Huron

Lake effect squalls off Georgian Bay and Lake Huron develop due to the northwesterly flow after the passage of a synoptic low over the area. These flows are generally parallel to the long axis of the open lakes moistening and deepening in the boundary layer producing bands of snowfall concentrated in a local area. An example of this is presented for an event on 18 January 2012. The surface air temperature was decreasing from -5$^\circ$C to -12$^\circ$C from 00 UTC to about 14 UTC and the 10m wind speeds varied from 2-8ms$^{-1}$ during this period. The wind direction ranged from 310-360$^\circ$. Figure 1 shows the 4-panel PPI at 0.3$^\circ$ elevation of $Z$, $Z_{DR}$, $\rho_{HV}$ and $K_{DP}$ at 12 UTC for this day.

Fig. 1 12 UTC 18 January 2012 PPI elevation at 0.3$^\circ$ of a) $Z$, b) $Z_{DR}$, c) $\rho_{HV}$, and d) $K_{DP}$.

The high reflectivity core is indicated by the line in Fig. 1a, along which the reflectivity values were in the 25-30dBZ
Lower reflectivity was observed away from the core. Z_{DR} ranged from 0-4dB in the band, but was generally lowest at the center of the band. Cross-correlation coefficients were above 0.95 and K_{DP} ranged from 0-0.5°/km. The local maximum of K_{DP}, of about 0.5°/km, was approximately 40km northwest of the radar in Fig. 1d. The band extended almost 100km inland from the lake shore and had a vertical depth of about 2.0km. The relatively shallow depth of these convective bands is also characteristic of these snow squalls. A sector encompassing the snow-band from 5 to 110km and 270° to 359° azimuth was selected and the mean of Z, Z_{DR}, and K_{DP} as a function of the perpendicular distance from the center of the band were calculated (Fig. 2).

The width of the band in this instance was about 20km. As reflectivity (thick line) decreased there was a small increase in Z_{DR} (thin line) with distance from the core shown in Fig. 2a. This feature is characteristic of most of the snow bands with the wind parallel to the long axis of the lake. The average K_{DP} variation with distance from the core as shown in Fig. 2b was small, reaching ~0.06°/km. The scatter plot of Z vs. Z_{DR} for this sector (5 - 110km, 270° - 359°) is shown in Fig. 3. Most pixels are distributed from 0-30dBZ with Z_{DR} in the range of 0-2dB. At higher Z there was a narrower range of Z_{DR}. The high Z_{DR} (>2dB as seen in Fig. 1b) pixels at the southeast edge of the band were not included in this figure.

The heaviest precipitation was at the core of the band with reflectivity approaching 35dBZ and oriented along the long axis of the lake. Compared to the northwesterly bands, this band is more elliptical in shape, shorter in extent and had higher core Z values. The bulk radar parameters are relatively symmetric about this core line and the perpendicular extent across the band was approximately 40km. In Fig. 4b the very high Z_{DR} (>3.0dB) along the north and south edges of the band suggest the presence of pristine crystals. Z_{DR} at the center of the band was near 0dB which implies the existence of graupel and rimed snowflakes.

Figure 5a shows the Doppler velocity pattern of the snow band over the lake. It shows the easterly propagation of the band and areas of convergence in the middle of the band. This is more clearly seen in the radial plot of velocity and reflectivity along the 146° azimuth in Fig. 5b. Along the radial at 40km from the radar, the velocity decreases by approximately 3m/s as the reflectivity increases with increasing range. The decreasing velocity at the core suggests convergence zones. The higher Z and lower Z_{DR} in the core of the band may be due to riming with the increased moisture availability from strong vertical motion in this region.

Fig 6 shows the mean Z, Z_{DR}, and K_{DP} as a function of the perpendicular distance from the center of the band. The highest reflectivity was at the center of the band and decreased with perpendicular distance from the core as Z_{DR} increased. Z_{DR} at the edges of the band were as high as 4dB with corresponding Z in the 5-10dBZ range. K_{DP} increased to about 0.2°/km further
away from the core as $Z_{DR}$ increased and $Z$ decreased.

![Fig. 4 PPI of a) Z and b) $Z_{DR}$ 15 UTC 12 February 2008.]

![Fig. 5 a) PPI of Doppler velocity and b) radial velocity(thick) and reflectivity(thin) along 146° azimuth at 15 UTC 12 February 2008.]

![Fig. 6 Averaged a) $Z$ (thick line), $Z_{DR}$ (thin line) and b) $K_{DP}$ as a function of perpendicular distance from the high reflectivity core of the snow band at 15 UTC 12 February 2008.]

![Fig. 7 Scatter plot of Z vs. $Z_{DR}$ at 15 UTC 12 February 2008.]

2.3) Synoptic snowfall

A synoptic low tracked across southern Ontario on 02 February 2011, leaving about 13cm of snow at the Toronto International airport, 35km south of the radar. The air temperature throughout the event was about -10°C and relative humidity close to 90%. Figure 8 shows the 4-panel PPI at 0.2° of $Z$, $Z_{DR}$, $\rho_{HV}$ and $K_{DP}$ at 1010 UTC for this day. The widespread storm showed a range of reflectivity values up to 40dBZ, while $Z_{DR}$ was in the range from 0-2dB. An interesting feature of this storm is the locally high values of $K_{DP}$ (0.5°-2.0°/km) in the north east sector of the radar where the reflectivity was relatively low (20-25dBZ). Also of note is the area at the tip of Georgian Bay where high $K_{DP}$ was associated with a narrow band of high $Z$ around 40dBZ.
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Figure 8 shows the scatter-plot of Z and Z\textsubscript{DR} and the distribution of K\textsubscript{DP} for the 1010 UTC 02 February 2011 event. The reflectivity ranged from 0-40dBZ, whereas Z\textsubscript{DR} remained relatively independent of Z. The peak of the distribution of K\textsubscript{DP} was at 0.1°/km while higher values above 0.5°/km were seen in the more intense regions of the storm. It is likely that in this case there was some lake effect enhancement of the snowfall at the southern shore of Georgian Bay.

3. Radar comparison with ground instrumentation.

The POSS at the CARE site provided information regarding precipitation rate and types as a time series. The radar beam for the lowest level PPI at 0.2° is approximately 300m above the site. Time series of radar data was extracted above the site and averaged over a 3x3 window. The radar time series of Z, Z\textsubscript{DR} and K\textsubscript{DP} are shown in Fig. 10 for the lake effect snow-band event for 18 January 2012. This band, shown in Fig. 1, persisted over CARE for several hours during the day. The band itself was only about 20km wide and changes in wind direction varied the snowfall intensity over CARE. During the period 00 UTC to 05 UTC, in Fig. 10a, Z\textsubscript{DR} generally varied from 0-1dB. During this period Z reached a maximum of 20dBZ at 0430 UTC and Z\textsubscript{DR} was almost 0dB. A similar inverse relationship between Z and Z\textsubscript{DR} was seen during 1030 UTC to 12 UTC.

Figure 10b shows the variation of K\textsubscript{DP} during the precipitation period. The K\textsubscript{DP} varied from 0°/km to 0.1°/km with peaks at about 03 UTC, 12 UTC and 13 UTC. K\textsubscript{DP} was almost zero during the period 1030 UTC to 1230 UTC, with Z reaching 25dBZ while Z\textsubscript{DR} was close to 0dB. The “effective” spherical snowflakes (aggregates, or rimmed crystals), though giving high Z due to large size but having Z\textsubscript{DR} “effectively” 0, did not contribute to K\textsubscript{DP} (Vivekananda et. al., 1994). At about 13 UTC K\textsubscript{DP} peaked to 1.0°/km whereas Z was almost 0dBZ and Z\textsubscript{DR} was around 0.6dB.

The bi-static nature of the POSS, with its non-uniform beam pattern, was used to explore the nature of the falling snow. The modes of these individual spectra, were summed in 1 minute increments (960 spectra). These plots, when combined with a forward scattering model of an equivalent solid ice sphere (Sheppard and Joe, 2007) are used to characterize the dominant precipitation particle in the sample volume. These are shown for a) 1145 UTC, and b) 1313 UTC in Fig. 11. At these times (vertical dotted lines in Fig 10a), the inverse relationship of Z and Z\textsubscript{DR} is most prominent. The modal output suggested plates or aggregates at 1145 UTC, with higher returned power and a fall speed of 1ms\textsuperscript{-1}. At 1313 UTC more crystals were suggested with lower fall speeds 0.7ms\textsuperscript{-1} and lower returned power. The solid ice diameter was 1mm and 0.4mm respectively at these times.
The synoptic snowfall event of 02 February 2011 also produced significant snowfall over the CARE site. The time series plot of the C-band radar parameters, Z, Z_{DR} and K_{DP} over this location are shown in Fig. 12.

For most of the storm, Z was in the range 10-30dBZ, and Z_{DR} varied between 0-1dB. As the low pressure system left the area, the wind shifted to a north westerly flow, thereby creating a condition for possibly lake effect enhancement off Georgian Bay. By 23 UTC the reflectivity had dropped drastically. There were significant variations in K_{DP} during the storm, Fig. 12b, with K_{DP} values being generally higher in areas with lake enhancement. K_{DP} peaked at 0.6°/km at about 0930 UTC. In Fig. 12b, during the period 11-16 UTC the lowest K_{DP} was associated with the lowest Z_{DR} in 12a.

The POSS modal spectral plots in Fig. 13 shows particle with fall speeds of 1.5ms^{-1} and 0.7ms^{-1} at 1602 UTC and 2108 UTC for 02 February 2011. The larger fall speed would suggest a larger denser rimmed particle with Z_{DR} closer to 0dB. This corresponds well with the low Z_{DR} high Z seen in Fig. 12a at 1602 UTC. At 2108 UTC however, the particle fall speed was only 0.7ms^{-1}, with Z_{DR} about 0.5dB and Z of 10dBZ (Fig. 12a) suggesting dendrites or irregular crystals.

The POSS also provided high temporal resolution of liquid equivalent precipitation rates for the different events at the CARE site. The precipitation rates were used as a reference for determining the relationship of Z and Z_{DR} with rate for the two types of event. Plots of POSS rate with spatially averaged radar Z and Z_{DR} are shown in Fig. 14. The POSS 1-minute rates were averaged over 10 minutes after adding a temporal offset to allow for the particle fall time from the radar volume.
The Z vs. Rate plots in 14a and 14b for both events showed a relatively high correlation with radar reflectivity, for both cases the correlation coefficient was around 0.8. The correlations of $Z_{DR}$ with precipitation rate were much weaker and negative for both storm types. The scatter was also much larger for $Z_{DR}$ vs. rate than for Z vs. rate. The lake effect case had a better correlation of $Z_{DR}$ with precipitation rate suggesting that a multi parameter QPE algorithm might be better in these cases than synoptic cases. For the synoptic snowfall case $Z_{DR}$ is not as correlated with precipitation rate and an algorithm that is based on Z and perhaps $K_{DP}$ might be better suited.

4. Summary and conclusions.

Snowfall events selected from several winter seasons were separated into three categories; northwest flow lake effect snow off Georgian Bay and Lake Huron, snow from easterly flows off Lake Ontario and large scale synoptic snowfall over southern Canada. High resolution low elevation PPI scans from the King City dual polarimetric C-band radar was used to describe each event type. The relationship between Z and $Z_{DR}$ showed significant differences between synoptic and lake effect events. Synoptic events had low $Z_{DR}$, generally between 0.0 and 1.0dB, extending over a wide range of Z from ~0-40dBZ. Lake effect bands showed a systematic inverse relationship between Z and $Z_{DR}$, with $Z_{DR}$ values of ~2-4dB being characteristic of low Z (~0-10dBZ). The high reflectivity cores, sometimes reaching 35dBZ, had $Z_{DR}$ values close to 0dB. The high Z/low $Z_{DR}$ cores in the middle of the lake effect bands were associated with convergence as deduced from the radial velocity patterns. Furthermore, there were differences in the lake effect bands, depending on their origin. Snow squalls that developed in easterly flows over Lake Ontario were shallower (~2.0km deep), more elliptical in shape and only extended a few 10’s of kilometers inland, compared to those that developed in a northwesterly flow off Georgian Bay or Lake Huron. The squalls that developed over Georgian Bay and Lake Huron were deeper (up to 3km) and sometimes extended to over 80km inland.

A POSS located at 34km/331° from the radar gave reference information about snow types and precipitation rates. Particle fall speeds from the POSS identified possible snow types at various times in each event and showed a range of particles, from pristine crystals, rimmed particles and aggregates. Variations of the radar measured $K_{DP}$ and $Z_{DR}$ were also related to these solid precipitation types. Relating Z and $Z_{DR}$ to rate at the surface showed potential for developing a snow rate algorithm based on event type. Additionally with the recent GPM Cold-season Precipitation Experiment (GCPEx) (http://pmm.nasa.gov/GCPEx) at CARE, supplemental ground information from a particle video imager (PVI), Parsivel, 2DVD disdrometer and manual gauge readings of event snow water equivalent accumulation, will be useful for the development of multi-parameter snowfall estimation algorithms for differing snow types.

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References


