

Cloud phase detection in winter stratiform clouds using Polarimetric Doppler Radar

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Abstract. The purpose of this study is to examine the radar signatures of two ground-based polarimetric radars, one S-band and one X-band, under winter storm conditions. A data set of coordinated ground radar and aircraft observations was collected during the Alliance Icing Research Study (AIRS) conducted in 1999/2000. Reflectivity values exhibit a strong relationship to the predominant phase and water content in the cloud system. Z_{DR} and k_{DP} contain valuable information for distinguishing mixed phase from glaciated conditions. In general, X-band k_{DP} 's are superior to S-band for these winter conditions. Insights into the results were obtained by examining the microphysical properties of the clouds as deduced from the in-situ aircraft measurements.

1 Introduction

Winter storms in southern Canada exhibit a wide variety of precipitation types (Stewart et al., 1990). This reflects a complex mixture of precipitation formation mechanisms that includes condensation, coalescence, accretion, ice multiplication, aggregation, melting, and freezing. The cloud systems contain liquid, glaciated and mixed phase regions, sometime in very close proximity to each other (Cober et al., 2001b). From the radar viewpoint, these storms are characterized by diffuse reflectivity patterns, that are considerably weaker than in summertime convection, rarely exceeding 30 dBZ. Existing particle typing algorithms (Vivekanandan et al., 1999) were developed primarily at S-band frequencies for summertime conditions where there are considerable in-situ verification data (e.g. Ellis et al., 2001). These algorithms offer limited usefulness when applied to winter conditions. The purpose of this study is to explore whether enhanced polarimetric radar signatures can be tied to specific microphysical processes under winter storm conditions and whether some polarimetric signatures are more pronounced at higher weather radar frequencies.

The Alliance Icing Research Study (AIRS), conducted during the winter of 1999/2000 in the area of Mirabel airport near Montreal, Quebec, provided a valuable data set of coordinated ground radar and aircraft observations with which to address these objectives. Details of the field project are contained in Isaac et al. (2001). Briefly, two research aircraft, the National Research Council of Canada Convair-580 and the NASA Twin Otter, collected in-situ data primarily in regions of the cloud system colder than 0°C. Flight maneuvers consisted of combinations of spiral descents overhead of Mirabel airport, missed approaches, and reciprocal runsflights at constant altitude on headings parallel to the runway at Mirabel, out to a range of 20 km. The polarimetric radar data were collected by two ground based systems, the McGill University S-band radar (MRO), located about 30 km south from Mirabel, and the McMaster University X-band portable radar (IPIX), located at Mirabel. The former system carried out regular volume scans during the experiment while the latter performed sector volume scans and stationary-antenna stares tailored to follow the research aircraft. This study focused on data from 9 days during the AIRS period in which significant cloud systems affected the Mirabel area.

2 Data collection and analysis

2.1 NRC Convair-580 cloud physics research aircraft

The aircraft in-situ microphysical data were averaged at 30 s resolution corresponding to a horizontal length of approximately 3 km. For each aircraft data point, the drop and ice crystal spectra were determined, and the cloud phase was identified and classified as liquid, mixed or glaciated. Details of the methodology are contained in Cober et al. (2001a). Reflectivities inferred from the ice crystal spectra were calculated following Heymsfield et al. (2002).

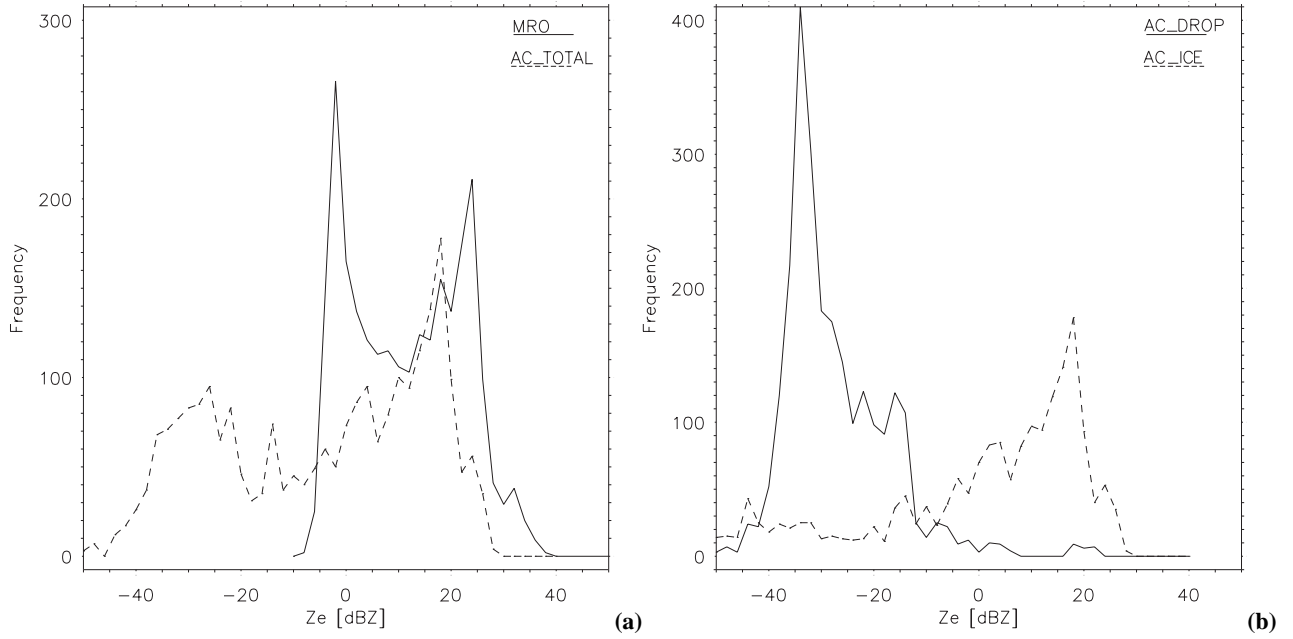


Fig. 1. The distribution of Ze during the AIRS aircraft operations. **(a)** (upper panel) Solid line is measured Ze from the S-band radar at McGill University (MRO). The dashed line is the calculated Ze from the aircraft-derived spectra (AC_TOTAL). **(b)** (lower panel) The dashed line represents the contribution by the ice portion of the aircraft-derived spectrum to the Ze calculation (AC_ICE), the solid line for the liquid portion of the spectrum (AC_DROP).

2.2 MRO S-band radar

The McGill University S-band radar employs a fast scanning strategy doing a full 24 elevation volume scan in 5 min. With range averaging, this amounts to about 20 independent samples per measurement at a resolution of 1 km in range and 1° in azimuth. The polarization scheme employed is the so-called slant 45 scheme, or hybrid mode as described in Bringi and Chandrasekar (2001). The specific differential phase values (k_{DP}) were obtained after averaging total differential phase (Φ_{DP}) over a running 5 km data window. Further information is contained in Zawadzki et al. (2001).

In matching the aircraft and radar data, the center of the aircraft swath and the center of the radar resolution volume had to be within 250 m. A 5×5 B-scan array of radar data around the acceptable resolution volume was considered in the subsequent analysis. Despiking techniques, frequently to remove the aircraft pixel, and removing data beyond one standard deviation of the median box value, were applied prior to the averaging of any radar parameter.

2.3 IPIX X-band radar

The McMaster University IPIX radar is a coherent polarimetric X-band radar. It uses fixed or alternating H or V transmission and dual-polarized reception. The data reported in this paper were taken with the antenna stationary, pointing either vertically or at various elevation angles along the azimuth of the aircraft reciprocals. The antenna pencil-beamwidth was 0.9 degrees, and the pulse length was 1 μ s. The total differ-

ential phase shift was first processed to mitigate the effects of backscatter differential phase shift in a manner similar to Bringi and Chandrasekar (2001). Then the k_{DP} values were obtained using least-squares fitting over a 4.7 km sliding window. A signal to noise ratio (SNR) threshold of 10 dB was used in the processing of the polarization parameters.

The IPIX radar collected full-bandwidth (5 MHz range sampling) for a two-second transmission burst approximately every 15 seconds, the intervening time used to permit storage of the data. All radar data for radar sampling locations within 2.0 km of the aircraft location, with less than 500 m vertical separation, and within 30 s in time, were used. With this sampling strategy, on occasion there would be more than one qualifying radar measurement per aircraft data point.

3 Results

The solid line in Fig. 1a gives the overall frequency distribution of MRO reflectivity (Ze) at temperatures colder than 1°C for those data points that matched the aircraft location. The distribution is bimodal, with peaks at -4 dBZ (near the minimum detectable signal (MDS) at the range of Mirabel) and +24 dBZ. The dashed line in Fig. 1a is taken from the calculated Ze based on the spectra derived from the corresponding aircraft data. This distribution is also bimodal, but with the low reflectivity peak at a much smaller Ze. The aircraft-derived Ze's were then subdivided by the contribution of the water and ice portions of the spectrum (Fig. 1b). The maximum Ze's calculated from the liquid part of the spectrum

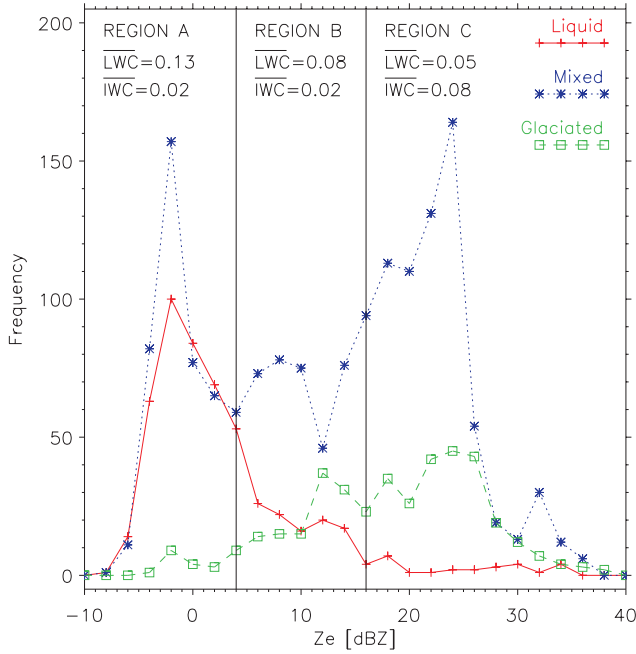


Fig. 2. The partition of the MRO Ze distribution in Fig. 1 by particle phase as deduced from an analysis of the aircraft in-situ data. Also indicated is the mean liquid water content (LWC) and ice water content (IWC) in g m^{-3} .

are generally less than the MDS of the MRO radar. Consequently, any Ze's measurable by the MRO radar were caused by ice particles. In 71% of the aircraft observations of liquid only clouds, there were valid MRO data. The implication is that even in portions of the cloud identified as liquid by the aircraft analysis, there is frequently still sufficient ice within the radar volume to give a valid MRO measurement.

This discrepancy stems from the sensitivity limit of the MRO radar and the mismatch in sampling volumes between the aircraft and radar sampling. For the 30 s analysis strategy employed by the aircraft analysis, a typical sample volume for the measurement probes is $4\text{--}5\text{ m}^3$. The radar sampling volume is some 9 orders of magnitude greater. As an illustration of the problem, a 2 mm diameter ice particle with a concentration of 0.1 m^{-3} , or a 3 mm particle with a concentration of 0.01 m^{-3} would give a reflectivity of about 0.0 dBZ. The aircraft sampling could easily miss these low concentrations of particles, yet they are significant for the radar measurements. At the higher end of the Ze distribution, the aircraft-derived Ze's are lower than those measured by radar (Fig. 1a). This suggests that the aircraft analysis is under-representing the larger particles.

The MRO Ze distribution in Fig. 1a was subdivided according to the phase assessment of the corresponding aircraft data (Cober et al., 2001a). Each valid MRO Ze was classified as representing liquid, mixed phase, or glaciated parts of the cloud system. The results are given in Fig. 2. The distribution can be divided into three distinct areas. Region A is the weak Ze region, i.e. $\text{Ze} < 4.0\text{ dBZ}$. Region B has intermediate Ze

values, i.e. $4 < \text{Ze} < 16\text{ dBZ}$. Region C has $\text{Ze} > 16\text{ dBZ}$. Region A contains liquid and mixed phase clouds. Region B contains all three phases. Region C is comprised primarily of mixed phase and glaciated portions of the cloud system. An examination of the water content and the measured radar reflectivity was carried out. The average ice water contents (IWC) were 0.02, 0.02, and 0.08 g m^{-3} for regions A to C, respectively. For liquid water contents (LWC), the averages were 0.13, 0.08, and 0.05 g m^{-3} . In general, there is a direct relationship between Ze and IWC and an inverse relationship between Ze and LWC.

The radar polarization parameters Z_{DR} and k_{DP} were examined to see if there was any additional information that could be of use in separating the different phases of the cloud system in the three regions of Fig. 2. It is noteworthy that since both the MRO and IPIX sets of radar data were matched to the aircraft data separately, the points in the scatterplot for the two radars are not necessarily the same aircraft data points. Ze values in Region A were generally too low to get reliable polarization estimates. In Region B, both radars showed that Z_{DR} was the most useful discriminator. Z_{DR} values show a trend towards higher values in the mixed phase regions than in the glaciated regions (Fig. 3a and b). For the S-band radar, k_{DP} was rather noisy and scattered around 0.0° km^{-1} . For the X-band, k_{DP} values were low, but measurable. They showed no distinction between mixed phase and glaciated phase conditions. In Region C, there is no such discrimination in Z_{DR} (Fig. 3c and d). For the S-band radar, there is no discriminating information in k_{DP} either. The S-band k_{DP} data are very noisy, likely a consequence of the relatively small number of samples per measurement due to the rapid scanning of the antenna. But for the higher frequency IPIX radar, the mixed phase region shows decidedly larger values for k_{DP} . With the X-band data, there is a preferred region for mixed phase conditions with $Z_{DR} > 0.5\text{ dB}$ and $k_{DP} > 0.1^\circ\text{ km}^{-1}$. Table 1 contains a summary of the polarimetric parameters by region for glaciated and mixed phase categories.

Insights into these results can be obtained by examining the microphysical properties of the clouds as deduced from the in-situ measurements corresponding to the regions defined in Fig. 2 (Table 2). There were too few data of glaciated cases in Region A or liquid in Region C. In Region A, LWC is large and comparable for liquid and mixed phase categories. The liquid part has more of the drops in larger sizes - the presence of large drops inferred from spectra with liquid $\text{Ze} > -10\text{ dBZ}$. The mixed phase has modest ice concentrations and a low but measurable IWC. The mixed phase and liquid portions in Region A are indistinguishable by the MRO radar.

In Region B, the liquid phase has higher LWC than in Region A and a significant proportion of the drops in the larger sizes. Mixed phase has slightly less LWC than the liquid phase, IWC comparable to the mixed phase region A, and ice concentrations slightly higher. The glaciated phase has much higher ice concentrations and higher IWC than mixed phase for the same region. The mixed phase could be asso-

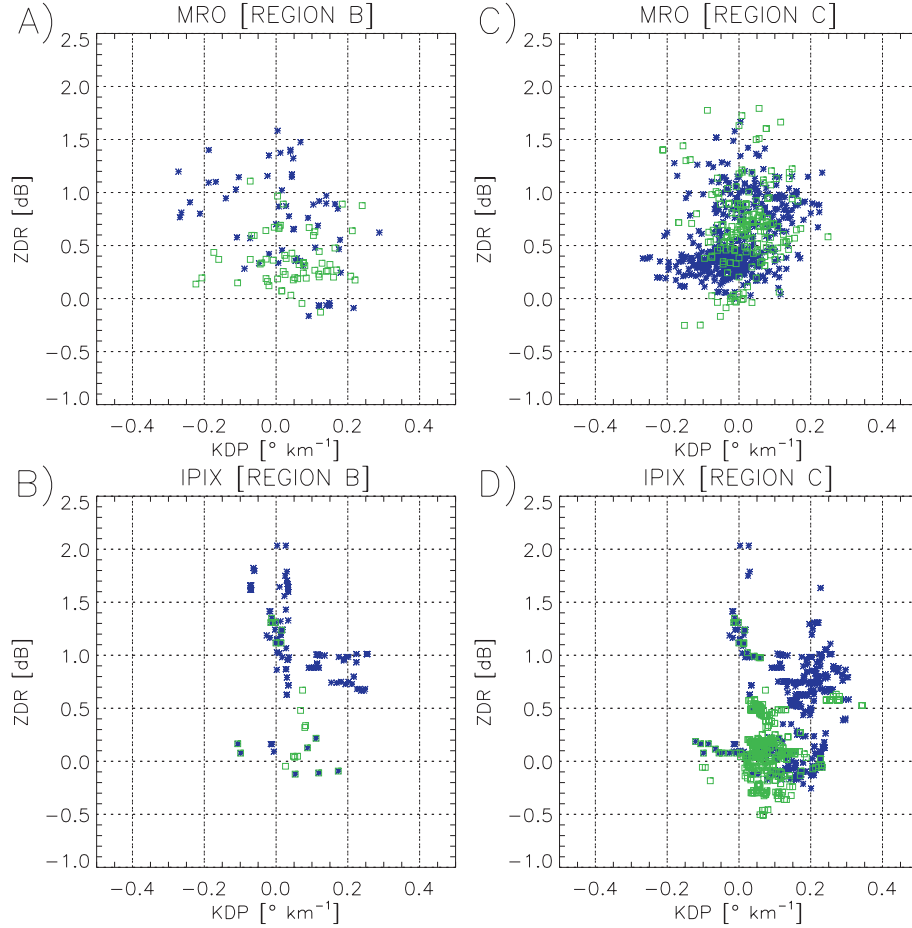


Fig. 3. A scatterplot of Z_{DR} vs. k_{DP} in mixed phase (blue asterisks) and glaciated (green squares) conditions for regions B and C from Fig. 2.

ciated with an active accretion process with modest amounts of ice but most of the mass in liquid form (Table 2). The ice particles under these conditions apparently have a preferred shape and orientation that gave relatively large Z_{DR} values. That Z_{DR} for the glaciated region is lower suggests that either the ice particles had an irregular shape or did not have a preferred orientation. There was not sufficient water mass in either category to give a significant k_{DP} value.

In Region C, mixed phase particles have increased in concentration and IWC. Mixed phase also has a significant amount of the LWC in the larger drop sizes. There was an equal proportion of mass split between IWC and LWC. Glaciated regions, on the other hand, were slightly lower in particle concentration but higher in IWC than in Region B. Z_{DR} was no longer a useful discriminator with either radar. With the increased ice mass in both mixed phase and glaciated conditions, particle shapes were similar. The glaciated regions were most likely experiencing aggregation of the ice into snowflakes. The mixed phase with an equal split of LWC and IWC and a significant amount of LWC in the larger drops probably had a complex mix of processes including accretion, aggregation and ice multiplication. Hudak et al. (2001) documented such conditions during one of the

AIRS flights. However, the increased mass in mixed phase resulted in increases in the k_{DP} values for the X-band radar. The S-band still did not measure any k_{DP} values significantly different from zero.

4 Summary

The main findings from the AIRS field studies are:

- The Ze distribution in winter storms exhibits a strong bimodality.
- The MRO reflectivity measurements are solely from ice particles in the cloud system.
- There is a direct relationship between Ze and IWC, and an inverse relationship between Ze and LWC.
- Z_{DR} and k_{DP} contain valuable information for distinguishing mixed phase from glaciated conditions. In general, X-band k_{DP} 's are superior to S-band for these winter conditions.

Table 1. A summary of the polarimetric parameters in regions B and C of Fig. 2

		Region B		Region C	
		Mixed phase	Glaciated	Mixed phase	Glaciated
Z_{DR}	MRO	0.7	0.4	0.6	0.7
(dB)	IPIX	1.1	0.5	0.4	0.2
k_{DP}	MRO	~ 0	~ 0	~ 0	~ 0
($^{\circ}$ km $^{-1}$)	IPIX	0.04	0.03	0.12	0.10

Table 2. A summary of average aircraft measured cloud properties for the three regions in Fig. 2

Region A			Region B			Region C		
	Liquid	Mixed Phase	Liquid	Mixed Phase	Glaciated	Mixed Phase	Glaciated	
Ice Concentration (l^{-1})	< 1	5.3	< 1	6.2	9.9	8.8	7.6	
Drop Concentration (cm^{-3})	24.2	39.6	24.2	31.3	< 5	27.7	< 5	
LWC ($g\ m^{-3}$)	0.12	0.14	0.15	0.09	~ 0.0	0.07	~ 0.0	
IWC ($g\ m^{-3}$)	~ 0.0	0.03	~ 0.0	0.01	0.06	0.07	0.10	
% of Obs with Liquid Ze > -10 dBZ	10	1	19	2	0	5	0	

Further work should also consider the information contained in the correlation coefficient parameter (ρ_{HV}) in developing algorithms that relate polarimetric radar signatures to specific microphysical processes. However, the complex relationship between cloud phase and radar observables shown in this study suggests that particle type membership functions in the form of beta functions (Bringi and Chandrasekar, 2001) may not be adequate.

The degree to which polarization weather radars can discriminate the cloud phase can have a profound impact in a number of areas. These include the development of algorithms to identify aircraft in-flight icing hazards and in the development of more effective microphysical parameterizations of important precipitation formation mechanisms in numerical weather prediction models.

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