Comparison of Airborne W-band Radar and In-situ Cloud Microphysics Data during AIRS II: Nov 11, 2003 Case

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1 Introduction

Research aircraft that are equipped with in-situ cloud microphysics probes and millimeter radars, similar to the one used in this study, provide coincident and closely spaced radar and cloud microphysics dataset (e.g., Wolde and Vali 2002), which will be very useful to develop and validate radar based cloud microphysics retrieval methodologies using space and ground based radars. This paper presents a comparison of an airborne radar and in-situ data collected in one of the flights during the second Alliance Icing Research Study (AIRS II) that was conducted between November 2003 and February 2004 over the Mirabel airport near Montreal, Canada and the surrounding regions in Ontario and Quebec. AIRS II was an international collaborative aircraft icing study using arrays of ground-based and airborne in-situ and remote-sensing instruments (Isaac et al. 2005). One of the scientific objectives of AIRS II was to develop techniques for identification of cloud particle compositions using remote sensors. The data used in this paper were collected on November 11, 2003, during which the NRC Convair aircraft sampled clouds consisting of glaciated, mixed phase and supercooled layers. The ultimate objective of this research is to determine the radar signatures of different cloud particle types based on the radar and in-situ data analysis, and to develop automated microphysical retrieval algorithm from radar data.

2 NRC Convair-580 AIRS II instrumentation

The NRC Convair-580 is a twin-engine turboprop aircraft that is extensively modified by the National Research Council (NRC) and Environment Canada for cloud physics research. During AIRS II, the aircraft was instrumented with arrays of cloud physics probes, aircraft and atmospheric state parameter sensors, and a Ka and W-band cloud radars. This paper focuses on the W-band radar data, liquid water content (LWC) measured by a King probe, PMS 2D-C particle image, and temperature measurements.

The airborne W-band radar system referred to in this paper is that of the University of Wyoming W-band Cloud Radar (WCR), which was installed on the NRC Convair-580 during the 1st IOP of AIRS II (Wolde et al. 2005). Detailed information on the WCR can be found from Pazmany et al. (1994). The Convair WCR installation included a side-looking 12” dual-polarized antenna and a down-looking single polarization 12” antenna. The WCR range samplings were set between 15 and 75 m with a maximum radar range of 1.5-7.5 km. The first usable radar range gate varies from 60 - 105 m. The radar sensitivity at one km is close to –30 dBZ while the cross-polarization isolation was better than –30 dB. The radar observables that are used in this paper are radar reflectivity factor (Z), differential reflectivity (ZDR) and linear depolarization ratio (LDR). Definitions of these radar parameters and their dependence on the cloud microphysical properties (size, shape, and phase of cloud particles) can be found in Bringi and Chandraseker (2001).

3 November 11, 2003 Case

Isaac et al. (2005) discussed the prevalent synoptic condition of the November 11, 2003 case and summarised the evolution of the cloud systems using airborne microphysical measurements and ground radars and radiometer measurements. The Convair-580 sampled glaciated cloud volumes consisting of various shapes ranging from irregular types at temperature of -22°C and hexagonal plate and needle crystals around temperature of -15°C and -5°C respectively.

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The Convair also encountered moderate to severe icing regions consisting of supercooled drizzle with LWC of up to ~0.5 gm^{-3}. In the following discussion we present the vertical and horizontal cloud structures observed by the WCR and how the radar data are related to the in-situ cloud microphysical properties.

3.1 Vertical cloud structure

The WCR data collected during the horizontal transect over Mirabel at ~6 km altitude show two distinct cloud layers with the top layer extending from the flight level to ~4 km and lower cloud layer extending from ground to ~3.5 km altitude (Fig. 1). The aircraft then made repeated horizontal transects inside the lower cloud layer. Fig. 2 shows vertical profiles of LWC and radar observables averaged over a 100 m vertical resolution. The top layer is fully glaciated with irregular types at T of -22°C to -19°C. The layer average Z values in this glaciated cloud range from 0 to 10 dBZ with ZDR and LDR of 0 dB and –25 dB respectively. At the base of the top cloud layer, the aircraft sampled pockets of hexagonal plates and dendrite type crystals at T of -15°C. The average Z values in this planar crystal dominated layer range from 0 to 10 dBZ with layer average ZDR and LDR values of 1-2 dB and –27 to –23 dB respectively.

As seen from the vertical profile of the LWC (Fig. 2), the lower cloud deck consisted of supercooled liquid clouds and mixed phase regions with layer average LWC of 0.05 to up to 0.3 g m^{-3} just above the melting layer located at approximately 1 km altitude. As the aircraft entered the top of the lower cloud layer, it encountered moderate icing conditions with layer average LWC of up to 0.2 g m^{-3}. This ~500 m thick supercooled cloud layer at T of –10°C to –8°C show distinctly different radar signatures than the glaciated cloud measured at the top cloud layer. In the supercooled layer, the layer average Z values dropped to –20 dBZ, with 0 dB ZDR and no detectable LDR.

As the aircraft descended further into the middle of the lower

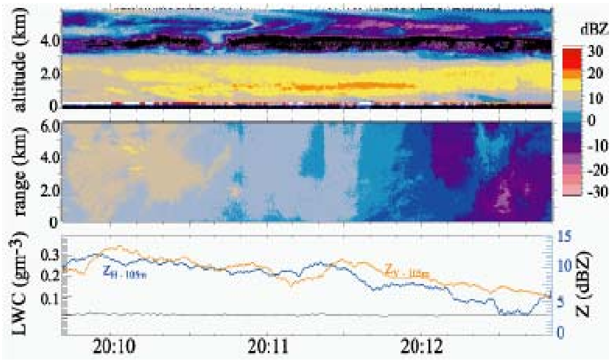

Fig. 1. Vertical (top) and horizontal (middle) profiles of radar reflectivity (Z) measured by the WCR during a horizontal transect at an altitude of 6 km. The bottom panel show traces of Z at 105 horizontal and vertical range from the aircraft and LWC data.

cloud layer, it encountered layers of needle-dominated regions (T = –6 to –4C), which also consisted of supercooled cloud drops and pockets of freezing drizzle. The radar measurement in this needle-dominated mixed phase cloud show Z values 0 to 10 dBZ and ZDR of 0-1 dB and LDR of –25 dB. The aircraft then entered into ~300 m thick isothermal layer with mixed phase conditions and high LWC. There is a sharp drop in both ZDR and LDR values in this layer. The ZDR value in this layer is centred at -1.5 dB, which can not be easily explained. Further down in the melting layer, the layer average LDR reach to a maximum value of -15 dB.

3.2. Transition zones

The layer averaged radar data and in-situ data presented in the previous section, although very informative in determining the vertical cloud stratification, mask the detail of the horizontal variability of the clouds sampled during the aircraft descent to lower altitudes. For example, the layer average of LWC (Fig. 2) suggests a mixed phase conditions throughout the lower cloud layer. However, as the data presented in this section show (Fig. 3-5), the clouds exhibit a

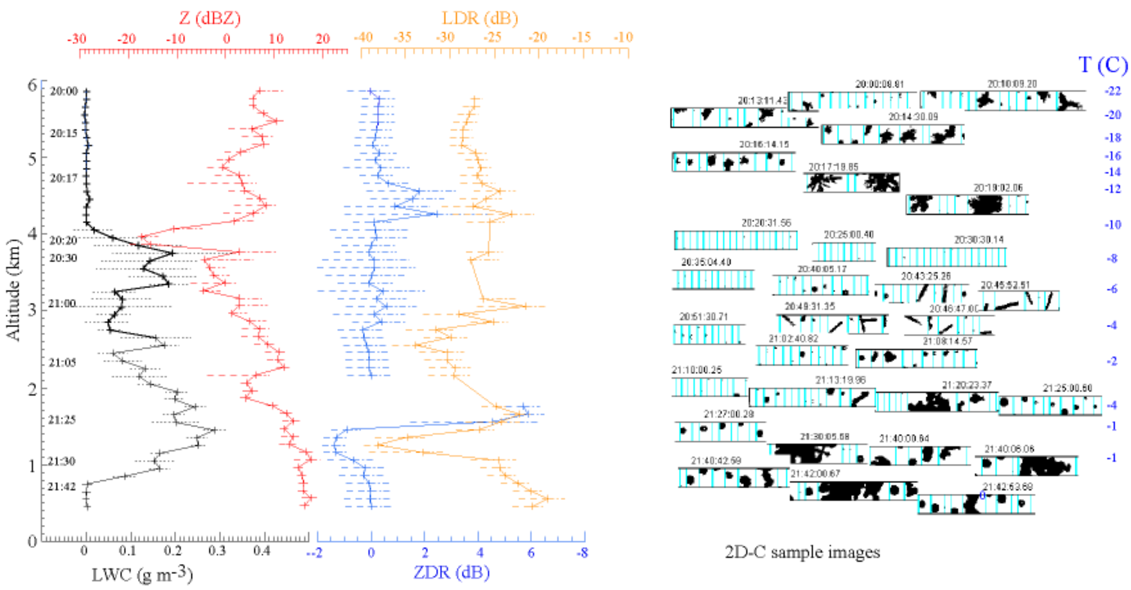

Fig. 2. Vertical profiles of LWC, Z, ZDR and LDR obtained by averaging the data over 100 m height. The error bar show one standard deviation of the data. The radar data are obtained from ranges close to the aircraft (60-105 m). Samples of 2D-C images showing types of particles sampled as the aircraft descended from a 6 km to 0.5 km height. The temperature and the time (20:00-21:42 UTC) are also listed for reference.

fine-scale horizontal variability in which pockets of glaciated and supercooled liquid hydrometeors exist side by side. In other words, when averaging is done in a vertical layer, the clouds appear as mixed phase.

3.2.1. Plates to Liquid

Fig. 3a. shows radar images of Z, ZDR, and LDR and traces of LWC, and Fig. 3b show frequency distribution of radar observables at the 60 m range measured as the aircraft descended from plate crystal regions at 4.2 km to supercooled liquids regions at 3.9 km. In the plate region, the Z field is relatively uniform with Z centred at 0 dB. The ZDR is centred at 0 dB, but with maximum of up to 6 dB in few pockets were observed. The LDR is centred at -27 dB. In contrast, in the supercooled regions, the Z is centred at –20 dB with 0 ZDR and no measurable LDR. Thus there is clear separation in the radar response in transiting from planar crystal region to supercooled regions. Based on the radar signature of supercooled regions, the liquid layer (weak Z and 0 ZDR) appears to extend to ~500 m from the cloud top (20:18:30-20:20:30).

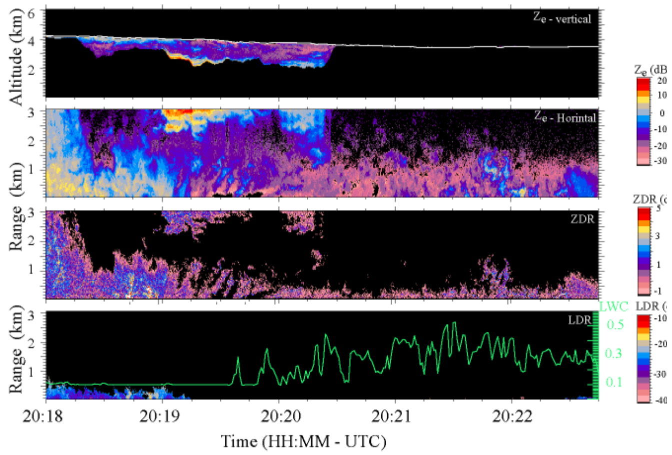

Fig. 3a. Vertical projection of Z (top) and Z, ZDR and LDR images from the side-looking antenna and traces of LWC (bottom panel) obtained as the aircraft descended from 4 km to 3.8 km.

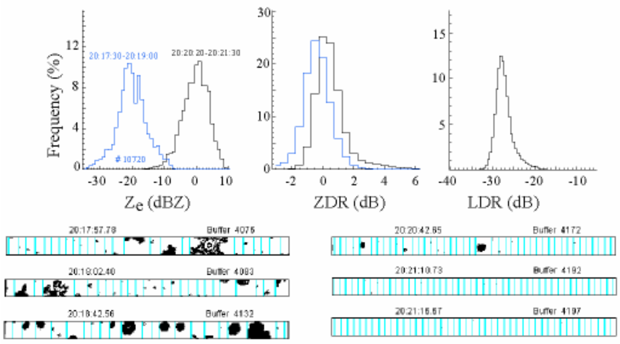

Fig. 3b. Histogram of Z, ZDR and LDR of the radar measurement at 60 m range and samples of the 2D-C images showing hexagonal and supercooled drops.

3.2.2. Supercooled liquid to Needle transitions

Fig. 4 shows histograms of the radar measurements at 105 m range obtained as the aircraft descended from 3.5 km to 3 km (refer to Fig. 2). During this time, the aircraft sampled supercooled drops and freezing drizzle, mixed phase and needle type crystals. The higher Z mode centred at –20 and the higher LDR peak centred at –20 dB correspond to measurement from cloud volumes dominated by needle crystals while the lower Z centred at -30 dBZ and the lower LDR mode centred at –30 dB is from mixed phase clouds composed of mainly supercooled drops.

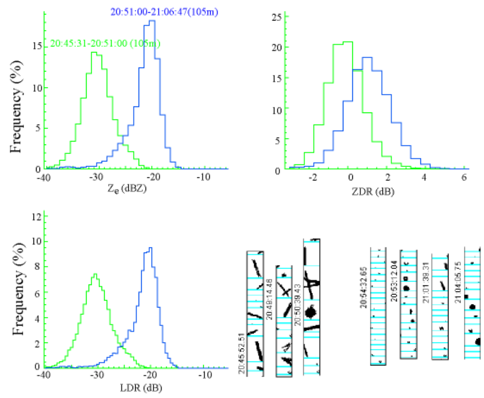

Fig. 4. Relative frequency distribution of Z, ZDR, and LDR obtained in needle regions and in supercooled drops.

3.2.3. Freezing drizzle and mixed phase cloud

Fig. 5 shows horizontal reflectivity profile obtained at an altitude of ~3 km and T of –4°C. Traces of LWC and radar observables (Z, ZDR and LDR) at the 105 m range from the aircraft and examples of the 2D-C images are also shown. The Z values show high horizontal variability with ranges from –20 dBZ to 10 dBZ. The Z variability and the wave-like cloud organization are also seen in the LWC measurement. The LWC varies from near 0.05 g m^{-3} in weak Z regions to 0.3 g m^{-3} in the high Z regions showing the fine-scale horizontal variability in Z, which is also exhibited in the LWC. The ZDR is generally stays near 0 dB, but there are narrow pockets (<100 m) that appear as spikes in Fig. 5

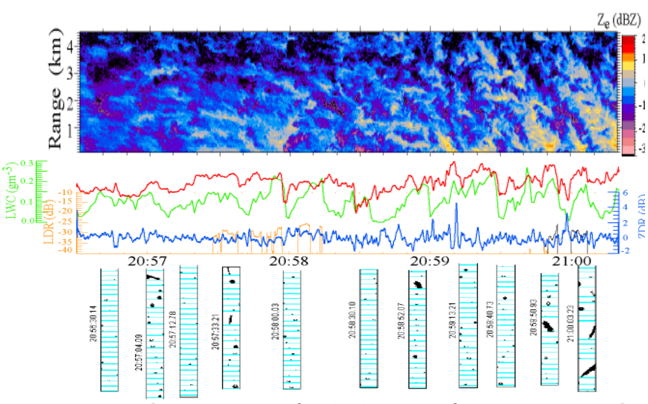

Fig. 5. Horizontal cross-section of Z (top), traces of Z, ZDR, LDR and LWC. Examples of 2D-C images are also shown.

where ZDR of 2-4 dB are observed. The high ZDR correspond to pockets of needle crystals. The LDR values in this freezing drizzle/mixed phase dominated cloud volume are generally below the detection limit of -30 dB.

3.3. Overall statistics

In an attempt to determine the overall statistics of the radar signatures of the different particle types the particle data are classified into four different categories (needle, circular and crystals (other than needles) and out of focus particles). In processing the radar data to determine the overall radar statistics, only segments with more than 75% of the particles classified as one of the four particle types are selected for processing. The frequency distribution of Z, ZDR and LDR for all the particle types-needles, circular and crystals (other than needles) are presented in Fig. 6 and also listed in Table 1. In all particle categories, the Z shows a bi-modal distribution indicating that the classification algorithm is broad and groups particles with distinct radar signatures in the same group. For example the 'circular' types have two distinct modes in Z centered at -20 and 10 dBZ, which corresponds to supercooled liquid and drizzle and rain drops respectively. In the same category, all the points with LDR ~ -30 dB (the minimum detectable LDR) corresponds to the larger drops. As shown in the Table 1, segments with homogenous cloud particle types selected subjectively from the 2D images show more distinct radar signatures than obtained from the automatic classifications.

Table 1. Summaries (mean/standard deviation) of radar measurements collected during the Nov 11, 2003 NRC Convair flight during AIRS II.

Time (UTC)	type	Z (dBZ)	ZDR (dB)	LDR (dB)
19:17-22:33	All	2.4/6.6	1.1/1.6	-22.1/4.5
	All	-2.7/10.8	0.6/1.5	-23.8/4.2
	Circular	6.5/11.2	-1.1/ 0.7	-33.8 /3.3
	Crystal	-10.3/10.1	0.1/0.9	-27.7/1.8
	Needle	-15.0/6.2	0.5/1.3	N/D
20:18:41-20:18:43	Plates	-1.1/1.6	5.1/1.8	-21.2/3.0
		2.1/2.5	3.4/1.7	-21.3/2.8
20:34-20:41	Liquid	-10.8/6.2	0.3/1.1	-33.1/13.0
20:45:31-20:48:00	Needle	-7.6/3.6	1.7/1.0	-19.7/2.4
20:57-21:06	mixed	-3.1/3.1	1.2/0.9	-23.2/2.1
21:44:30-21:44:50	Melting crystals	15.7 / 0.7	0.2/1.0	-14.8/2.5

4 Summary

This paper compares airborne W-band radar with in-situ microphysical data collected on November 11, 2003 during the AIRS II experiment. This preliminary analysis show:

- Pristine ice crystals (plates and needles) and melting crystals can be identified by their unique polarimetric signatures. This agrees with earlier observations reported by Wolde and Vali (2002).

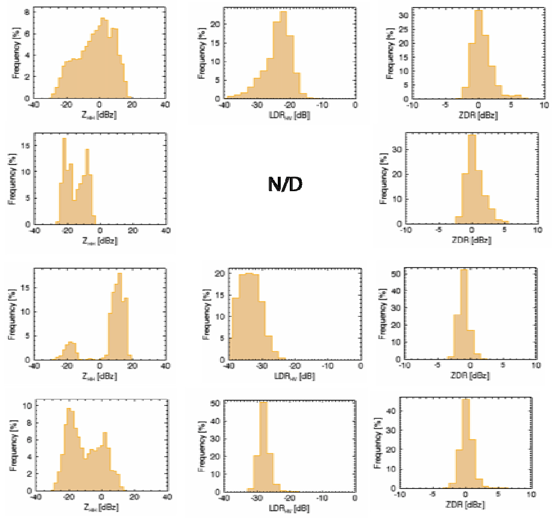

Fig. 6. Histograms of Z (left), ZDR (middle) and LDR (right) at 60-105 m range from the aircraft. Rows from top to bottom are for: all types, needle, circular and crystals types.

- The bimodal distribution of Z observed in the clouds that contain supercooled liquids and ice crystals or large drizzle drops is similar to the findings by Hudak et al. (2002) using ground based radar and Z computed from aircraft data.
- There is significant variability both in vertical and horizontal cloud structure, and averaging of the data masks the fine-scale cloud structure observed in the sampled clouds.
- More robust automatic classification of the in-situ particle types is required to cover more particle types than what is used in this study.

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