Preliminary Results from the Alliance Icing Research Study (AIRS)

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Abstract

The Alliance Icing Research Study (AIRS) field project was conducted between 29 November 1999 and 19 February 2000. The main objectives of AIRS are 1) to improve our ability to remotely sense aircraft icing regions using satellite, aircraft or ground based systems; 2) to obtain additional data to characterize the icing environment which might be used in a revision of "Appendix C", the criteria used to certify aircraft for icing conditions; and 3) to improve our ability to forecast icing conditions and to understand how these conditions develop. An extensive array of remote sensing equipment was based at Mirabel airport to the north of Montreal. This instrumentation included five microwave radiometers, X-Band dual polarised scanning Doppler radar, X-Band vertically pointing Doppler radar, W-Band scanning Doppler radar, Ka-Band scanning Doppler radar, and a multiple field of view scanning polarised LIDAR. In addition, a scanning dual polarised S-band radar was operating at Ste. Anne de Bellevue, about 30 km SSE of Mirabel. The project aircraft were based out of Ottawa and flew most of their missions over the remote sensing equipment at Mirabel. The NRC Convair-580, the NASA Glenn Twin Otter, and a Learjet-25 operated by SPEC flew 25, 16 and 4 flights respectively. The Convair experienced 3 runback, 2-3 tail plane and 3-4 moderate-severe icing events. Icing was encountered on 4-5 flights with ambient temperatures colder than -20^{o}C. One Convair severe icing event over Mirabel, associated with small droplets, occurred at -29^{o}C. The Twin Otter saw moderate-severe icing on 2 days. In general, an excellent data set was obtained, that will provide good inter-comparisons between the aircraft in-situ measurements and the remote sensing data from Mirabel. The data will allow characterizations of the remote sensing instruments with respect to their abilities to detect and measure icing environments. Ultimately, this should allow for the design and development of advanced airport weather warning systems.

Introduction

The Alliance Icing Research Study (AIRS) was conducted between 29 November 1999 and 19 February 2000. It was a joint project involving several research organisations, with the core agencies including the Meteorological Service of Canada (MSC), National Research Council (NRC), NASA Glenn, Federal Aviation Administration (FAA) and Transport Canada (TC). The Canadian Space Agency (CSA) and the Defence Research Establishment at Valcartier (DREV) also provided funding. This was the first study being performed as part of the Aircraft Icing Research Alliance (AIRA). It should provide the aviation industry in general some very useful data, and this data should lead to products, that will improve aviation safety.

The main objectives of the project, in order of priority, were 1) to improve our ability to remotely sense aircraft icing regions using satellite, aircraft or ground based systems, 2) to obtain additional data to characterize the icing environment which might be used in a revision of "FAR 25 Appendix C", the criteria used to certify aircraft for icing conditions, 3) to improve our ability to forecast icing conditions and to understand how these conditions develop, and 4) to obtain measurements of aircraft performance within icing conditions and shapes of ice accretion that might be used in verification of icing model codes or in wind tunnel studies that simulate icing conditions. Because of limited flight hours, the 4th objective was barely addressed.

The project aircraft, which were based in Ottawa, Ontario, included the NRC Convair-580, the NASA Glenn Twin Otter, and a Learjet-25 operated by Stratton Park Engineering Corporation (SPEC) of Colorado. An extensive array of remote sensing equipment was based at Mirabel airport to the north of Montreal, Quebec. This instrumentation included five microwave radiometers, X-Band dual polarised scanning Doppler radar, X-Band vertically pointing Doppler radar, W-Band scanning Doppler radar, Ka-Band scanning Doppler radar, and a multiple field of view scanning polarised LIDAR. In addition, a scanning dual polarised S-band radar was operating at Ste. Anne de Bellevue, about 30 km SSE of Mirabel. The Convair-580 flew 25 flights (87.6 h), 18 of them over Mirabel. There were 16 flights with the NASA Twin Otter (24.2 h), and 4 flights with the Learjet.

All the data obtained during this study will be archived and made available to the community after appropriate quality control is performed, and after the participants have had an opportunity to examine and publish summaries of their data. This purpose of this paper is to outline some of the first results from the project.

Climatology

Severe icing is expected to occur with supercooled large drops (SLD), or freezing drizzle and freezing precipitation. A surface climatology has been conducted to get an estimate of where such hazardous conditions occur with the highest frequency. Within North America, maxima in the occurrence of freezing precipitation occur near St. John's, Newfoundland, and near the Great Lakes area (Strapp et al., 1996; Stuart and Isaac, 1999). Near St. John's, the 30 year long record shows freezing precipitation occurs approximately 150 hours per year, while in the Great Lakes area, there are maxima near 75 hours per year. Previous to this study, the collaborators conducted two major studies in the field of aircraft icing. The Canadian Freezing Drizzle Experiment I (CFDE I) was based near St. John's, but CFDE III was moved to the Ottawa area to examine conditions in continental clouds where air traffic was much greater than on the Canadian east coast (see Isaac et al. 1999). AIRS operated in a similar area to CFDE III with the remote sensing equipment being located at Mirabel. Table 1 shows that Mirabel is located in a high frequency zone for freezing rain (ZR) and freezing drizzle (ZL), and it is near the 75 hour per year maximum. Dorval, just to the south of Mirabel, has considerably less freezing precipitation, while Ottawa experiences conditions like those at Mirabel. December appears to be the best month, followed by January and February.

Climatology results are averages over a long period, in this case 30 years. However, special conditions do occur. During January 1998, the great Ice Storm hit southern Ontario and Quebec and freezing precipitation lasted for most of a week. The data of Table 1 do not contain that episode. Table 1 shows conditions as observed at the surface, and it is expected that freezing precipitation occurs aloft at these sites more frequently than at the surface.

Location	Nov	Dec	Jan	Feb	Mar	
Ottawa	9 4	21 11	12 6	10 5	11 5	ZR+ZL ZL
Mirabel	12 3	24 11	10 5	12 6	12 4	ZR+ZL ZL
St. Agathe	14 5	26 14	16 10	9 5	13 6	ZR+ZL ZL
Dorval	4 2	17 8	8 3	8 4	8 3	ZR+ZL ZL

Table 1: A 30-year climatology of freezing precipitation in hours per month for Ottawa, Mirabel, St. Agathe and Dorval. ZR-freezing rain, ZL- freezing drizzle.

Data from a detailed study performed for Transport Canada, and summarized by Stuart and Isaac (1994), on the winter hazards at Canadian airports showed that that snow occurred approximately 20% of the hours during these winter months at Mirabel. Freezing precipitation (defined as the combination of freezing rain, freezing drizzle and ice pellets) did not show a strong diurnal variation, with 29%, 24%, 21% and 26% occurring during the intervals 00-05, 06-11, 12-17, and 18-23 LST respectively. Ice pellets are included in this definition of freezing precipitation because they often indicate the presence of freezing drizzle or freezing rain aloft. Most of the freezing precipitation fell at the temperature range 0 to -10^{o}C with the majority occurring at temperatures between 0 and -5 ^{o}C. Both dry snow and freezing precipitation occur with a maximum frequency with winds from the NE. The percentage of hours with dry snow with winds from the NE, is 42%, 43% and 38% for December, January and February, respectively, of the total number of hours with dry snow. The percentage of hours with freezing precipitation with winds from the NE, is 81%, 80% and 78% for December, January and February, respectively, of the total number of hours with freezing precipitation. This remarkable correlation with wind direction is probably related to the St. Lawrence Valley orientation, and either cold air pooling in the valley, or upslope conditions caused by the walls of the valley.

Parameter	NRC Convair-580	NASA Twin Otter	SPEC Learjet-25
Temperature	Rosemount (x2), Reverse Flow, Haman High Frequency Probe	Rosemount 102	Rosemount 102
Dewpoint	EG&G Cambridge, LI-COR	General Eastern	EG&G Cambridge
Pressure (True Airspeed Barometric Alt.) Accelerations Angle of Attack Attitude and Rates	Paroscientific Series 1000 Litton 9100 IRS Rosemount 858,	Rosemount 542K Rosemount 542K Sundstrand QA-700 Rosemount 858	Rosemount 1201 Rosemount 1221 Systron-Donner 4310A-3-B Lear P/N 819802-2 Northrop GR-G5A-1.0L
Navigation	IRS Litton 90-100 GPS Novatel (x2), Trimble	Ship heading gyro Trimbull TNL-2000 GPS	Learjet Sperry gyro Garmen GPS-92
Liquid/Total Water	CSIRO King LWC (x2) Nevzorov TWC/LWC	CSIRO King LWC Nevzorov TWC/LWC	CSIRO King LWC Nevzorov TWC/LWC Lear Engine Temp.
Aerosol	PMS PCASP 100 0.1-3 μm		
Droplets	PMS FSSP 100 3-45 μm PMS FSSP 100 5-95 μm	PMS FSSP 3-47 μm	FSSP 100
Hydrometeors	PMS 2DC Mono 25-800 μm PMS 2D-2C Mono 25-800 μm PMS 2DC Grey 25-1600 μm PMS 2DP Mono 200-6400 DRI Cloudscope DRI Replicator SPEC Cloud Particle Imager	PMS 2D-G 15-960 μm	PMS 2DC Mono 25-800 μm SPEC Cloud Particle Imager
Remote Sensing	SATCOM Satellite Receiver 3 cm Aircraft Weather Radar MSC LIDAR (1064 nm) Ka-Band Cloud Radar IR pyrgeometer (up and down) Visible pyranometer (up and down) Trent FTS		
Icing	Rosemount 871FA Vibro-meter Icing Detector Airbus Certification Cylinder Rosemount SLD Icing Detector SATCOM Radome Video	Rosemount 871FA Wing stereo photo Over wing video Tail video	Rosemount 871FA

Table 2: Instrumentation on the three project aircraft for AIRS. Not all instruments were flown at the same time in the case of the Convair-580.

Instrumentation

The three project aircraft had substantially different instrumentation as indicated in Table 2. The Convair-580 (Cober et el., 2001a) was primarily equiped for cloud microphysical and remote sensing measurements. The Twin Otter (Miller et al., 1998) has an equipment suite, which allows aircraft performance to be accurately monitored as the aircraft picks up ice. The Learjet-25 main task was to monitor cloud microphysical conditions as it climbed up the beam of the ground based radar located alongside the Mirabel runway. Only a high performance aircraft such as a Learjet could perform this task.

Most of the ground based remote sensing instruments (Table 3) were located at Mirabel airport north of Montreal. However, there were a few instruments located at the hangar site at Ottawa, and the McGill University scanning S band radar located at St. Anne de Bellevue also played an important role. An upper air sounding system was also operated at Mirabel during intensive observing periods.

Most of the Convair, and all of the Twin Otter and Lear missions, were made in the vicinity of the Mirabel remote sensing equipment. Some (7 of 25) of the Convair flights were made to areas, not necessarily near Mirabel, where it was expected that moderate to severe icing could be encountered. This was to collect further characterization data (Objective 2) and to validate forecasts (Objective 3).

Ground Based Remote Sensing Instruments

- MSC Attex 37/85 GHz radiometers, dual polarisation (Ottawa);
- Attex un-manned 37 GHz radiometers (Mirabel);
- Radiometrics frequency scanning (22-30 GHz, 51-59 GHz) radiometers for vertical profiles of LWC and T, and LWP and WVP (Mirabel);
- FAA un-manned Radiometrics 23.8/31.4 GHz radiometer (Mirabel);
- Russian 22/37/131 GHz non-polarised scanning radiometers (Mirabel);
- McMaster X-band dual polarised scanning Doppler radar (Mirabel);
- McGill X-band vertically pointing Doppler radar (Mirabel);
- McGill 915 MHz UHF wind profiler (Montreal);
- McGill S-band, dual polarised, scanning Doppler radar (St. Anne de Bellevue);
- DREV multiple field of view scanning polarised LIDAR (Mirabel);
- U. Massachusetts W-band scanning Doppler radar (Mirabel);
- U. Massachusetts Ka-band scanning Doppler radar (Mirabel);
- MSC Class radiosonde system (confirmed only for occasional use) (Mirabel);
- SPEC Ka-band and X-band steerable radars (Mirabel).
- Trent FTS spectrometer (Mirabel)

Table 3: Ground based remote sensing instruments and their location during AIRS.

In-Cloud: T<0 ^{o}C	Convair	Twin Otter
30 s Points	3259	1354
Liquid	27%	64%
Mixed	50%	31%
Glaciated	23%	5%

Table 4: In-cloud data for the Convair and Twin Otter sorted by percentage of time in liquid, mixed and glaciated phases as defined by Cober et al. (2001b). It uses data from the Rosemount icing detector (Cober et al., 2001c) as well as the PMS FSSP and 2D probes.

	1 %	25 %	50 %	75 %	99 %
Twin Otter	**Points = 836**	**Ta ≤ 0°C**		**I ≤ 1 L^{-1}**	
Ta (°C)	-12.3	-7.6	-4.9	-2.6	0.0
Nd (cm^{-3})	3	28	64	140	196
TWC (g m^{-3})	0.01	0.05	0.11	0.19	0.45
MedVD (μm)	10	14	17	24	68
	1 %	25 %	50 %	75 %	99 %
Convair	**Points = 1519**	**Ta ≤ 0°C**		**I ≤ 1 L^{-1}**	
Ta (°C)	-28.8	-10.5	-7.7	-5.4	-1.0
Nd (cm^{-3})	2	50	110	201	645
TWC (g m^{-3})	0.01	0.04	0.09	0.18	0.42
MedVD (μm)	10	12	15	20	211

Table 5: Twin Otter and Convair percentile values of in-cloud parameters at temperatures colder than 0^{o}C and with ice crystal concentrations (I) less than 1 L^{-1}. Ta, Nd, TWC and MedVD refer to temperature, droplet concentration, total water content and median volume diameter respectively. As an example, 25% of the Twin Otter droplet concentrations were less than 28 cm^{-3}.

Summary of Aircraft Data

Summaries of the 30-s averaged in-cloud data of both the Convair and the Twin Otter are given in Tables 4 and 5. A 30-s average represents a distance of 3 km and 2 km respectively for the Convair and the Twin Otter.

Tables 4 and 5 show that the Convair flew more often in glaciated cloud than did the Twin Otter, likely due to its flying at generally colder temperatures. In addition, during December, the only month when the Twin Otter flew, all liquid clouds seemed to be more frequent. A substantial portion of both the Convair and Twin Otter data were obtained in mixed phase clouds as defined by Cober et al. (2001b) with both liquid and ice being present in substantial concentrations. The median liquid water content was approximately 0.1 g m^{-3} for both aircraft, and the droplet concentrations were typically 100 cm^{-3} or lower.

Figure 1 shows the Convair and Twin Otter cloud liquid water content plotted against the median volume diameter for the 30-s in-cloud averages with ice crystal concentrations less than 1 L^{-1}. The Newton (Newton, 1978) curves for his defined severe (12 g cm^{-2} h^{-1}), moderate (6 g cm^{-2} h^{-1}) and light (1 g cm^{-2} h^{-1}) icing conditions are plotted in Figure 1. In addition, the FAA Regulation 25 Appendix C (FAR 25-C) envelopes (Federal Aviation Administration, 1999) for 0°C, -10°C and –20°C have been plotted. It should be remembered that although Figure 1 is similar to the FAR 25 Appendix C conditions, those conditions end at 50 µm and the averaging period is approximately 30 km. If the current data were averaged for 30 km, there would be fewer points and the data would have lower liquid water contents. However, Figure 1 shows that a substantial fraction of the data set has median volume diameters greater than Appendix C conditions. Figure 2 shows only the data where SLD (drops > 50 µm) was encountered. It should be noted that although SLD was encountered, the median volume diameter can be less than 50 µm. The case studies which will be discussed later are indicated by the letters A,B, C and D.

Case Studies

a) Twin Otter: 10 December – Severe Icing

On 10 December over Mirabel, the Twin Otter encountered severe icing near 12,700 ft at temperatures between –7 to –9 °C. The icing occurred in a region of non-classical freezing drizzle (drops formed without going through an ice phase) above a glaciated layer. A typical 30 s spectra during the icing is shown in Figure 3, while a photograph of the Twin Otter's wing leading edge and a specially painted surface underneath the wing is shown in Figure 4.

The liquid water contents were 0.1 to 0.3 g m-3 during this encounter, with a substantial fraction of the liquid water in the drizzle size range (MedVD 60 µm). Icing was occurring aft of the leading edge boots.

After seven minutes (14:54 to 15:01 UTC) in this icing condition, the increased drag caused a 15 knot decrease in indicated airspeed with the same power setting. This airspeed loss occurred even with the deicing boots cycling automatically every 3 minutes. During the spiral over Mirabel, a warm layer was encountered which removed all residual ice from the airframe. Subsequent encounters of the SLD icing conditions at 12,700 ft had less effect on the aircraft performance.

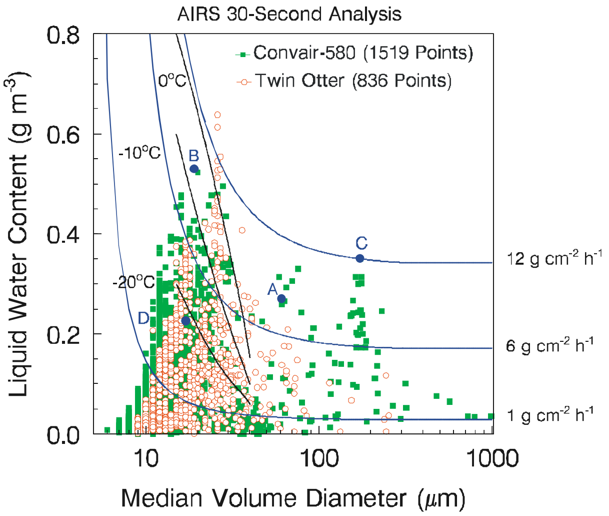

Figure 1: Convair and Twin Otter data plotted against liquid water content and median volume diameter. The FAR 25 icing envelopes and Newton's curves, which define the severity of icing conditions, are also plotted.. The data represent cases with Ta # 0°C and I # 1 L^{-1}. The case studies of 10 December/99, 16 December/99, 25 January/00 and 16 February/00 are indicated by the letters A,B C and D respectively.

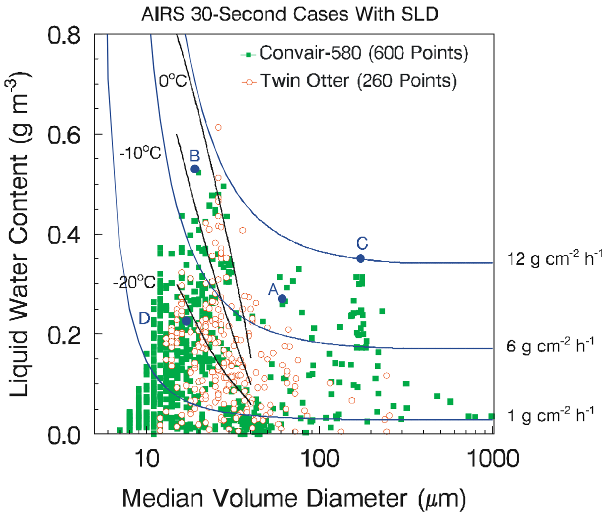

Figure 2: As in Figure 1, except only using cases where SLD (drops >50 µm) were present.

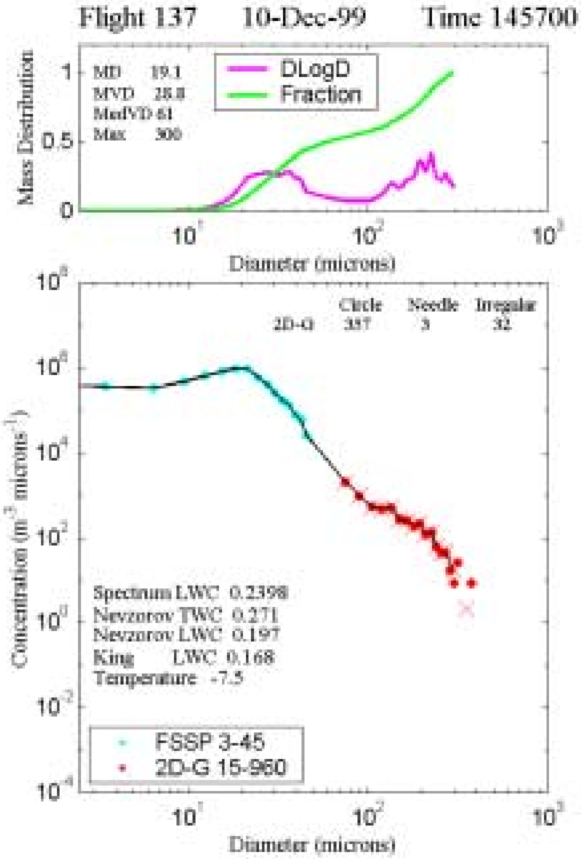

Figure 3: A 30-s averaged particle spectra obtained at 14:57 UTC during the severe icing episode encountered by the Twin Otter on 10 December. The top panel shows the relative mass distribution (DlogD) plotted against drop size, as well as the cumulative mass distribution. Also shown are the mean diameter (MD), the mean volume diameter (MVD), the median volume diameter (MedVD) and the maximum observed diameter (Max). All sizes are in microns. The bottom panel shows the particle or drop size number distribution as determined by PMS FSSP and 2D-G probes. The liquid water content calculated by integrating the spectrum (Spectum LWC), the Nevzorov probe total water content (TWC), the Nevzorov probe LWC (Korolev et al., 1998), the King LWC are shown in g m^{-3}. The data were obtained at –7.5 ^{o}C.

Figure 4: Photo taken 10 December at 15:14 UTC of the Twin Otter right wing inboard of the engine nacelle.

Figure 5: A photo of the Convair-580 wing surface showing runback ice for the 16 December moderate icing episode. The heat duct on the leading edge of the wing extends only as far back as the painted black square mid-span on this photo.

b) Convair-580: 16 December - Moderate Icing

On 16 December while flying over Mirabel at 6,500 ft near –12°C, the Convair flew into moderate icing. This episode caused runback icing to occur aft of the anti-icing system (Figure 5). Figure 6 shows a typical particle spectra during the icing episode. Most of the cloud liquid water was in the small drop size less than 30 µm with a median volume diameter of 19 µm. However, it is interesting to note that some large irregular shaped ice crystals (100-1500 µm) were present as noted by the PMS 2D imaging probes. This was probably causing the radar echoes that were seen by the onboard Ka-band cloud radar (Figure 7). The radar image indicates that the radar reflectivity was cellular in nature, which suggests some local convection.

c) Convair-580: 25 January – Moderate to Severe Icing

On 25 January, at 10,000 ft near –11°C, the Convair-580 flew though a patch of freezing drizzle and the icing on the aircraft was categorized as moderate to severe by the pilots. Figure 8 shows the icing on the windscreen as it was photographed after the flight. Note that the side windows have a considerable amount of ice on them. Unfortunately, this flight was made after sunset and so the ice on the aircraft could not be photographed during the icing episode. Nevertheless, observations of an illuminated section of the upper surface of the wing made during the flight indicated that there was ice build up immediately aft of the heated leading edge. The estimated thickness of the ice was 1-3 cm. The accretion was similar to that indicated in Figure 15. The pilots estimated a drop in 20-30 knots in true airspeed during this encounter from what would be expected in this flight regime.

Figure 9 shows that the icing was encountered within a deep layer as seen by the McGill vertically pointing radar. This radar can be used to discriminate precipitation types based on the Doppler velocity signatures (Fabry and Zawadzki, 2000). The layer on 25 January was probably composed of large ice crystals as evidenced by the fall speeds detected with the Doppler radar and the reflectivity gradient between 3-4 km suggesting fast ice particle growth in a water saturated environment. The spectra of Figure 10 show most of the liquid mass in large drops with a median volume diameter of 170 µm. There also appeared to be a small concentration of large irregular ice crystals co-exiting with the supercooled large drops.

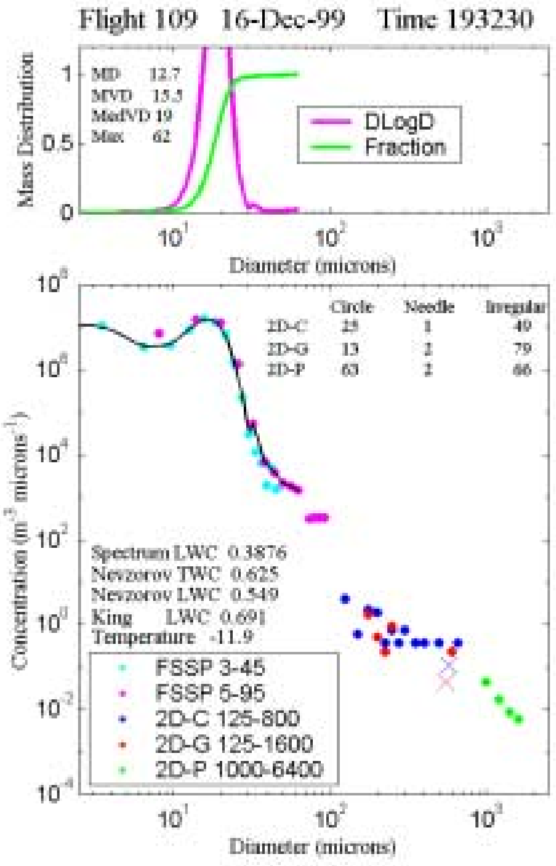

Figure 6: A 30-s spectra obtained onboard the Convair-580 on 16 December during a moderae icing episode. The symbols are as defined in Figure 2, except for the Convair, two PMS FSSP probes and three 2D probes are used to create the spectra.

Figure 11 shows the radiometer trace while the Convair was flying over Mirabel. At approximately the same time the aircraft encountered a high liquid water content zone with moderate to severe icing, the liquid water path reached a maximum. Figure 12 shows a McGill S-band 3 km CAPPI with the aircraft track plotted on top of the image. The maximum icing was observed southwest of Mirabel in a relatively weak echo region. Figure 13 shows the aircraft liquid water content and S-band reflectivity plotted for the NE-SW pass and demonstrates that lower reflectivities seem to coincide with higher liquid water contents. This is reasonable in that ice particles that are producing the radar echo tend to grow at the expense of the liquid water.

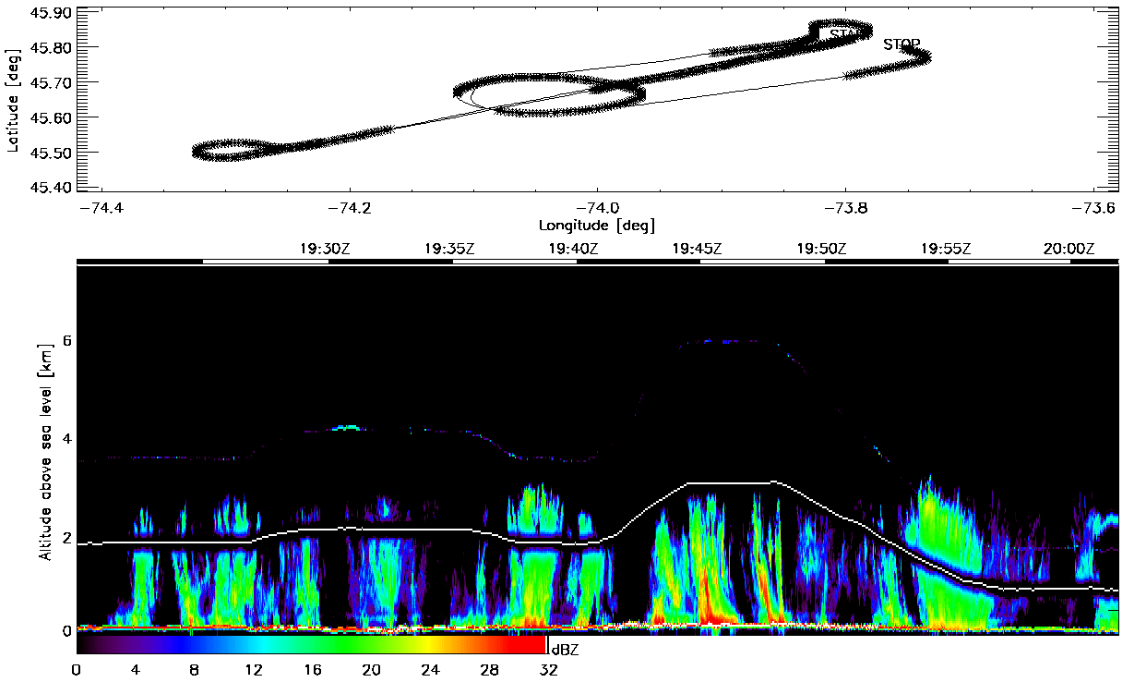

Figure 7: A time/altitude/reflectivity history on 16 December of the Convair's onboard radar which looks up and down (bottom panel). The white line indicates the altitude of the aircraft. The period of moderate icing occurred near 1932 UTC. The top panel shows a plan view of the aircraft's flight path as it flew over Mirabel.

Figure 8: Photo of the Convair windscreen after the icing event of 25 January. Note the ice located on the side windows. This picture was taken back in the hanger after the flight.

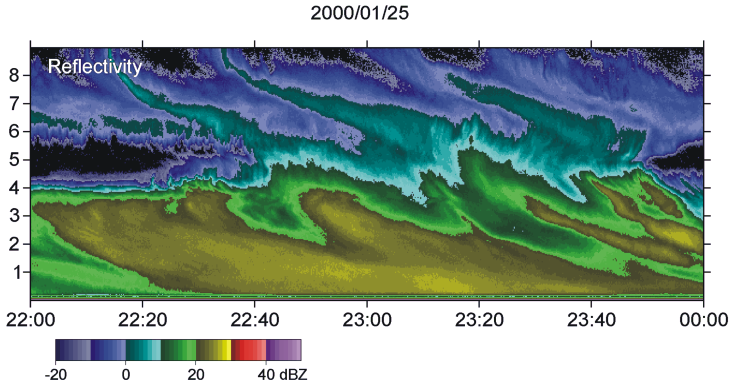

Figure 9: McGill vertically pointing radar reflectivity image for the 25 January icing event. The icing occurred at 3 km near 2230 UTC.

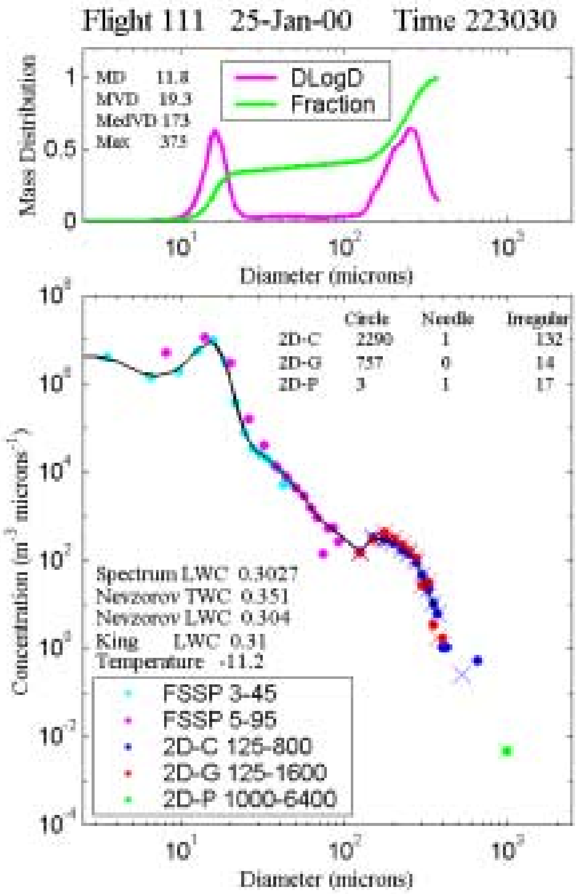

Figure 10: A 30-s spectra from data collected onboard the Convair-580 on 25 January during a severe icing episode. The symbols are as defined in Figure 2.

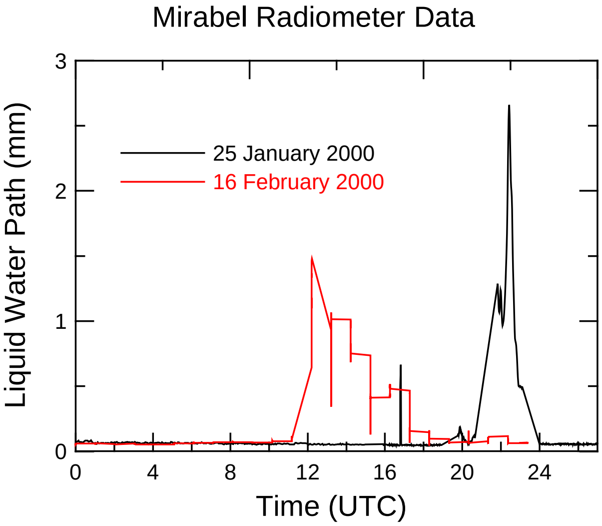

Figure 11: MSC vertically pointing radiometer data obtained at Mirabel for 25 January and 16 February 2000. The radiometer measures the vertically integrated liquid water path above the instrument in mm.

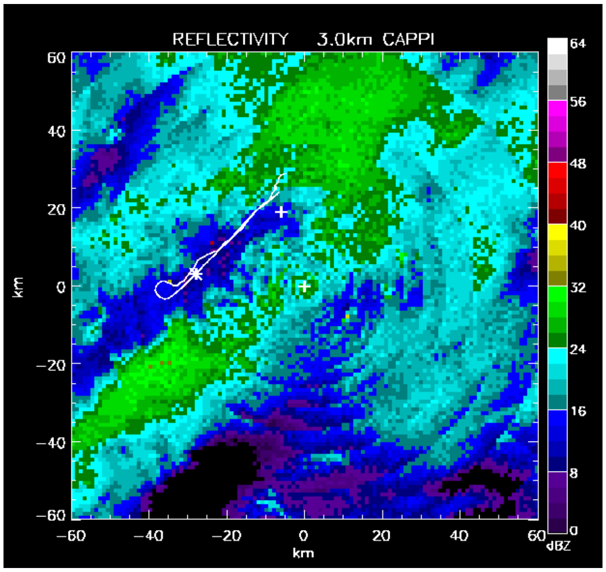

Figure 12: A 3-km CAPPI (Constant Altitude Plan Position Indicator) from the S-band McGill radar at 22:32 UTC on 25 January 2000. The Convair flight path is indicated, and the location of the icing at 22:30:30 UTC, Mirabel and the S-Band are indicated by *,+, and + symbols respectively.

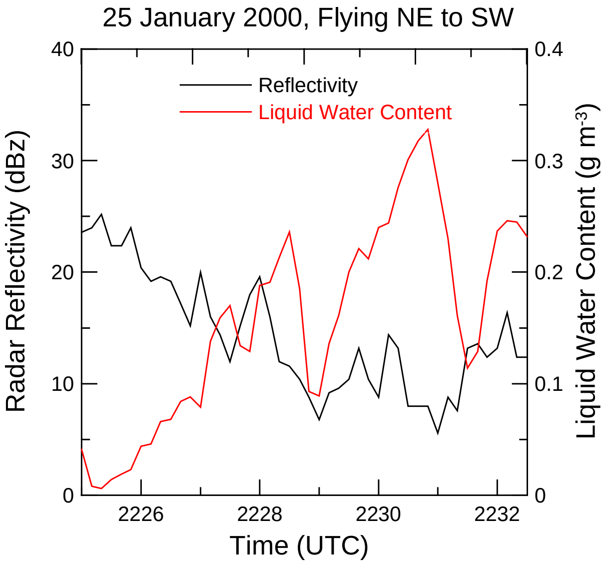

Figure 13: Reflectivity and liquid water content as a function of time for the NE to SW pass south of Mirabel as marked on Figure 12.

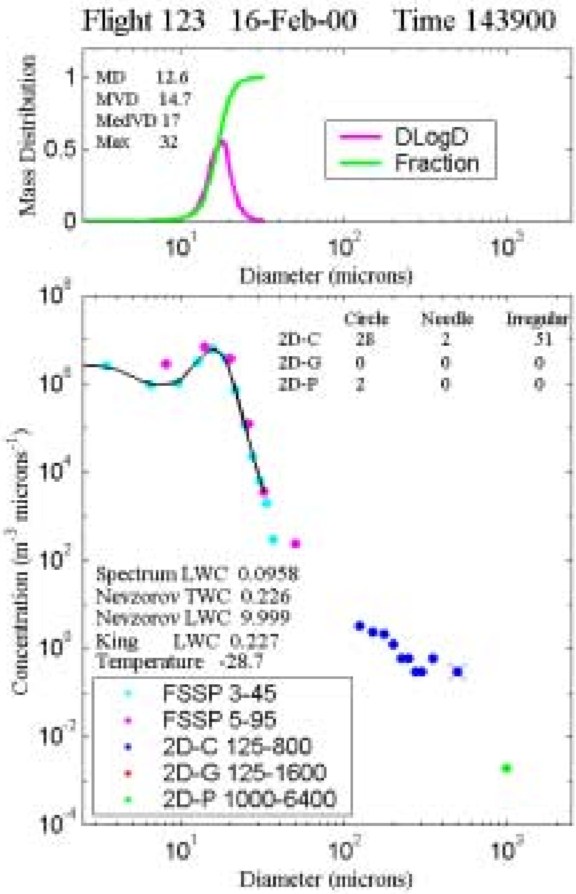

Figure 14: A 30-s spectra from data collected onboard the Convair-580 on 16 February during a severe icing episode. The symbols are as defined in Figures 2.

Figure 15: A photo of the Convair-580 showing runback ice close just aft of the heated leading edge of the wing for the severe icing episode of 16 February.

Figure 16: A photo of the Convair-580 horizontal stabilizer during the icing episode of 16 February.

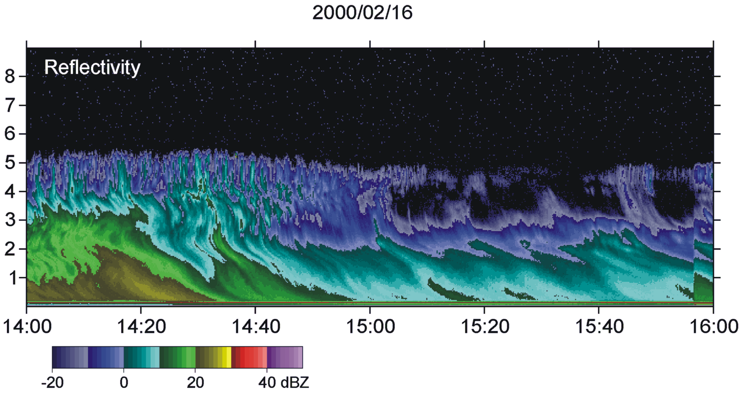

Figure 17: McGill vertically pointing radar for the Convair-580 severe icing episode of 16 February. Severe icing occurred near 14:39 UTC at 5.5 km.

d) Convair-58: 16 February – Severe Icing

The most severe icing episode for the Convair-580 occurred on 16 February over Mirabel at 18,000 ft at the very cold temperature of –29°C. Figure 14 shows that the liquid water contents were substantial (> 0.2 g m^{-3}) with most of the liquid occurring at small sizes (MedVD near 17 μm). Runback icing was observed near the leading edge of the wing (Figure 15), much further forward than for the –12°C case of 16 December (Figure 5). Ice appeared on the leading edge of the horizontal stabilizer completely covering over the heated surface (Figure 16). On descent to warmer temperatures, one could actually see water running underneath this ice surface, which tenaciously remained attached.

This encounter was severe enough that after 5 minutes of operating in these conditions the pilots first increased power by 20-30% to maintain the flight conditions and shortly after this decided to ascend above cloud (18,500 ft) to deice. In all probability, the very low temperatures that were encountered in this case rendered the thermal anti-icing system less effective than normal.

The McGill vertically pointing radar shows that the icing occurred on top of a deep layer of reflectivity probably caused by snow. Figure 14 indicates that the large particles seen at sizes greater than 100 μm were probably ice crystals because most of them had irregular shapes.

The icing occurred at the time when the radiometer was indicating a maximum liquid water path (Figure 11).

Discussion

The data described above represents only a small fraction of what was collected during AIRS. Some interesting and unique scientific measurements were made that were not mentioned. For example, a Desert Research Institute cloudscope was used to video the impact of ice particles onto a flat surface projected into the airstream. These images showed that many of these ice crystals stuck to the surface and did not bounce. This suggests that total water content, not simply liquid water content, may be a factor for consideration in the design of thermal ice protection systems.

If pilots are to know they are in SLD conditions, then an appropriate sensor must be developed. Such a commercial sensor was being tested during AIRS. A fast response temperature probe built in Poland (Haman et al., 1997) made measurements within the icing environments that will hopefully better explain why large drops form in supercooled clouds. Some early work, based on similar measurements from CFDE, has already been reported by Korolev and Isaac (2000).

It is necessary to better understand the formation of large drops before they can be accuaretely forecast. The data collected during this project will help formulate answers to this question. Although considerable progress has been made in forecasting icing conditions (Guan et al., 2001; Tremblay et al., 1995), and freezing precipitation (Tremblay and Glazer, 2000), much remains to be done. For example, it would be beneficial to have forecasts with some indication of icing severity, and whether conditions outside of "Appendix C" might be present. During AIRS some new forecast products both from MSC and NCAR were being tested in real-time and it is hoped that this will lead to new advances.

The following preliminary conclusions can be made from the initial data from AIRS which has been analyzed:

- The summary of the aircraft data (Tables 4 and 5) show that mixed phase clouds were often encountered. The median total cloud water content was approximately 0.1 g m^{-3} for both the Convair and Twin Otter data sets. The droplet concentrations tended to be low (50-100 cm^{-3}) for these continental clouds.
- Most of the supercooled large droplets observed formed through condensation/coalescence without going through the ice phase. In fact, 99 % of the SLD encountered by the Convair was formed through such a non-classical formation mechanism.
- Using the project aircraft, it was not unusual to find icing conditions , and even icing conditions with supercooled large droplets over Mirabel airport. An analysis of the project radiometer data will give a better climatology of how often supercooled water was observed.
- The radiometer shows potential for indicating the possible occurrence of icing (Figure 11). However, for the cases of 10 and 16 December, rain was falling at the surface and this made the radiometer measurements inaccurate.
- Icing environments, some of which were moderate-severe, were characterized using the Convair equipment, while the ground based remote sensing equipment at Mirabel was observing the same volume. This data should help develop an airport based system to warn of in-flight icing aloft.

- A comparison of the four moderate to severe icing episodes described in this paper show that they generally agree with the definitions of FAR-25 and Newton (1978) (see Figures 1 and 2). For the cases of 16 December and 16 February, the median volume diameters and liquid water contents exceed the FAR-25 envelopes. For 10 December and 25 January, these points lie between the moderate to severe definitions of Newton.
- As the data of Figures 3,6,10 and 14 show, there is an indication that large ice crystals were present during these moderate-severe icing episodes. Because radar reflectivities are related to the particle diameter to the 6th power, such large particles may dominate any radar signature. This may make it difficult to detect icing zones directly using conventional radars data. However, more sophisticated techniques, involving polarization diversity radar, and multi-frequency radar show promise at resolving this issue.

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