43rd AIAA Aerospace Sciences Meeting and Exhibit
10 - 13 January 2005, Reno, Nevada

AIAA 2005-252

First Results from the Alliance Icing Research Study II

G.A. Isaac[1], J.K. Ayers[2], M. Bailey[1], L. Bissonnette[3], B.C. Bernstein[4], S.G. Cober[1], N. Driedger[1],
W.F.J. Evans[5], F. Fabry[6], A. Glazer[1], I. Gultepe[1], J. Hallett[7], D. Hudak[1], A.V. Korolev[8]
D. Marcotte[9], P. Minnis[2], J. Murray[2], L. Nguyen[2], T.P. Ratvasky[10], A. Reehorst[10], J. Reid[1],
P. Rodriguez[1], T. Schneider[11], B.E. Sheppard[1], J.W. Strapp[1], and M. Wolde[9]

[1]*Meteorological Service of Canada, Toronto, Ontario*
[2]*NASA Langley Research Center, Hampton, Virginia*
[3]*Defence Research Development Centre, Valcartier, Quebec*
[4]*National Center for Atmospheric Research, Boulder, Colorado*
[5]*Trent University, Peterborough, Ontario*
[6]*McGill University, Montreal, Quebec*
[7]*Desert Research Institute, Reno, Nevada*
[8]*Sky Tech Research Inc., Richmond Hill, Ontario*
[9]*National Research Council, Ottawa, Ontario*
[10]*NASA Glenn Research Centre, Cleveland, Ohio*
[11]*NOAA-Environmental Technology Laboratory, Boulder, Colorado*

The field phase of the Second Alliance Icing Research Study (AIRS II) was conducted from November 2003 to February 2004, with the main center of interest being near Mirabel, Quebec. The AIRS II project operational objectives are to: a) develop techniques/systems to remotely detect, diagnose and forecast hazardous winter conditions at airports, b) improve weather forecasts of aircraft icing conditions, c) better characterize the aircraft-icing environment and d) improve our understanding of the icing process and its effect on aircraft. In order to support the operational objectives, the following science objectives are being addressed to: a) investigate the conditions associated with supercooled large drop formation, b) determine conditions governing cloud glaciation, c) document the spatial distribution of ice crystals and supercooled water and the conditions under which they co-exist, and d) verify the response of remote sensors to various cloud particles, and determine how this can be exploited to remotely determine cloud composition. Five research aircraft were involved in the field project. These aircraft flew special flight operations over a network of ground in-situ and remote-sensing meteorological measurement systems, located at Mirabel, Quebec. Data were collected to evaluate some prototype airport weather forecasting systems, which use satellite and surface-based remote sensors, PIREPS, and numerical forecast models. The project will also be used in North America and Europe to further develop numerical forecast models, and forecast systems, which predict aircraft icing over large areas. AIRS II is an exciting collaborative effort involving approximately 26 government and university groups from Canada, the United States and Europe. It will assist in providing the aviation community better tools to avoid aircraft icing, and to improve the efficiency of airport operations.

I. Introduction

The field phase of the Second Alliance Icing Research Study (AIRS II) was conducted during the winter of 2003/2004. AIRS II is a project endorsed by the Aircraft Icing Research Alliance (AIRA), which consists of government organizations interested in aircraft icing. It is also being supported by the World Meteorological Organization (WMO) World Weather Research Program (WWRP) project on Aircraft In-Flight Icing. The First Alliance Icing Research Study (Isaac et al., 2001a) occurred during December 1999 to February 2000 in the same

---

[1] Corrresponding author:: George A. Isaac
4905 Dufferin Street, Toronto, Ontario, Canada, M3H5T4. E-Mail: george.isaac@ec.gc.ca

area. This project used 3 aircraft stationed out of Ottawa and remote sensing hardware located at both Ottawa and Mirabel (see http://airs-icing.org/) to investigate the remote sensing of aircraft icing and other aircraft icing issues.

AIRS II, which builds on the results of AIRS I, has operational objectives to: a) develop techniques/systems to remotely detect, diagnose and forecast hazardous winter conditions at airports, b) improve weather forecasts of aircraft icing conditions, c) better characterize the aircraft-icing environment and d) improve our understanding of the icing process and its effect on aircraft. In order to support the operational objectives, the following science objectives will be addressed to: a) investigate the conditions associated with supercooled large drop formation, b) determine conditions governing cloud glaciation, c) document the spatial distribution of ice crystals and supercooled water and the conditions under which they co-exist, and d) verify the response of remote sensors to various cloud particles, and determine how this can be exploited to remotely determine cloud composition.

Five research aircraft were involved in the field project. The National Research Council Convair-580 and the NASA Glenn Research Center Twin Otter operated out of Ottawa, Ontario, the National Science Foundation C-130 from the National Center for Atmospheric Research (NCAR) operated out of Cleveland, Ohio, and the NASA ER-2 and the University of North Dakota Citation operated out of Bangor, Maine. These aircraft flew special flight operations over a network of ground in-situ and remote-sensing meteorological measurement systems, located at Mirabel. Data were collected to evaluate some prototype airport weather forecasting systems, which use satellite and surface-based remote sensors, PIREPS, and numerical forecast models. They include the Airport Vicinity Icing and Snow Advisor (AVISA) being developed at the Meteorological Service of Canada, the Icing Remote Sensing System (NIRSS) from NASA, and the Ground-based Remote Icing Detection System (GRIDS: Reinking et al., 2001) being developed by the National Oceanic and Atmospheric Administration. The aircraft also provided data to verify remote-sensing algorithms used to detect icing conditions. The project results will also be used in North America and Europe to further develop numerical forecast models, and forecast systems, which predict aircraft icing over large areas.

AIRS II is an exciting collaborative effort involving approximately 26 government and university groups from Canada, the United States and Europe. These participants are listed in Table 1. AIRS II will assist in providing the aviation community better tools to avoid aircraft icing, and to improve the efficiency of airport operations. It will also enable some unique basic science objectives to be addressed such as: how supercooled large drops form, how cloud ice forms, and how to better remotely detect cloud properties. This paper will describe the project and the associated instrumentation and it will present some preliminary results.

Canada	United States	Europe
Meteorological Service of Canada Institute for Aerospace Research, NRC Transport Canada Canadian National Search and Rescue Secretariat Defence Research and Development Canada - Valcartier McGill University Trent University Communication Research Centre Canadian Foundation for Climate and Atmospheric Sciences Natural Sciences and Engineering Research Council	NASA-Glenn and Langley Research Centers National Center for Atmospheric Research NOAA – Environmental Technology Laboratory Federal Aviation Administration National Science Foundation US Army Cold Regions Research and Engineering Laboratory CRREL Mount Washington Observatory Desert Research Institute University of Colorado Colorado State University Purdue University University of Illinois at Urbana-Champaign Oregon State University University of North Dakota	British Met Office Meteo-France

Table 1. Participating Organizations in AIRS II.

II. Surface Based Equipment and Aircraft

The list of ground based equipment used during the project is given in Table 2. There were two main sites at Mirabel Airport (CYMX). The “Tecksol Site” was primarily for the NASA and NOAA systems and was located 900 m off the main runway so that the radars for these systems could stare in the direction of the aircraft as they were making missed approaches. Most of the vertically staring equipment was located at the “Garage Site” which was located about 1.5 km away. The spiral ascents and descents over the airport were mainly made at this site.

Each aircraft had its own specialized list of equipment which would be difficult to list, so a brief description of each aircraft and its role is given below.

Convair-580: The NRC Convair-580 was extensively instrumented for cloud microphysical measurements and this equipment has been described by Isaac et al. (2001a,b). Cober et al. (2001) describe some of the analysis techniques used for processing this data. There was a concerted effort to make good cloud liquid water content measurements,

GROUND BASED EQUIPMENT		
Standalone Remote Sensing Equipment	**Owner/Operator**	**Remarks**
S-Band Dual Polarization Scanning Radar	McGill University	Located in Ste Anne de Bellevue
915 MHz Wind Profiler with RASS	McGill University	Located at McGill campus downtown
50 MHz VHF Profiler	McGill University	Located in Ste. Anne de Bellevue
Multiple Field of View, Dual Polarization Scanning Infrared Lidar (1.06 µm and 0.532 µm)	DRDC - Valcartier	
Fourier Transform Spectrometer	Trent University	Zenith Looking
Hyperspectral Imager	National Research Council	Pointing to SW at 45 degrees
Special Systems	**Owner/Operator**	**Remarks**
NASA NIRSS	**Prototype System Developed by NASA**	
Vertically pointing X-band radar		
TP-3000 profiling radiometer		
89/150 GHz profiling radiometer		
CT25K Ceilometer		
NOAA GRIDS	**Prototype System Developed by NOAA**	
Ka-band radar dual polarized		Scanning and Doppler capable
90 GHz radiometer		Data reliability questionable: estimates mean liquid temperature w/30 GHz
23.87/31.65 GHz radiometer		40 degree elevation, measures integrated water vapor and cloud liquid.
MSC AVISA	**Prototype System Developed by MSC**	
WVR-1100 radiometer	Mt. Washington Observatory	
Vertically Pointing X-band radar	McGill	
TP-3000 profiling radiometer	Communications Research Centre (CRC)	
Two Hot Plates		DRI/NCAR Design
Precipitation Occurrence Sensor System (POSS)		
CT25K Ceilometer		
Visibility Meter		
Pyranometers/Pyrgeometers		
Fog Measuring Device		
10 m Met Tower		
Wind Speed and Direction		
Temperature		
Pressure		
Humidity		
PRT-5 Precision Radiation Thermometer		Measures Cloud Base Temperature
Other Systems	**Owner/Operator**	**Remarks**
ASOS Ice Detector	CRREL	
Sippican Balloonsonde System	NASA-Glenn	
Precipitation Camera	McGill University	
POSS	McGill University	
Mesonetwork of Ground Sites	McGill University	For winds, temperature and precipitation
Video Surveillance Recordings	MSC	Trained on horizon and instrumentation

Table 2. List of ground based equipment used during AIRS II. Unless otherwise indicated, the equipment was located at the Mirabel airport site. Most of the equipment was located at the "Garage Site." However, the NASA NIRSS, the NOAA GRIDS and the McGill POSS were located at the "Tecksol Site."

so in addition to the normal Nevzorov Total Water and Liquid Water Content probe, and the King Probe, a new Science Engineering Associates (SEA) deep-fetch hot probe and a Desert Research Institute (DRI) T-Probe were installed on the aircraft. A prototype Sky Tech extinction probe was tested during this period. A high speed DRI cloudscope and replicator were also used in the wing tip pylon locations. A SPEC HVPS was installed to image the large particles that could affect radar reflectivity measurements. A British Met Office Small Ice Detector (SID-1) was also run during a portion of the project. Remote sensing measurements on the aircraft included recording the X-band aircraft weather avoidance radar, an SEA up and downward pointing Ka-Band radar, and a University of Wyoming W-band side and downward pointing radar. Trent University installed a Fourier Transform Spectrometer which looked up and down. The main role of the aircraft was to collect data over the Mirabel site in support of the Nowcasting systems located there. However, it also made several flights to other locations to collect more microphysical data to better characterize the in-flight icing environment, especially those related to supercooled large drops. Special maneuvers were made during flights to characterize the aircraft performance during icing conditions (see Brown, 2005).

Twin Otter: The NASA Twin Otter was instrumented with its standard cloud microphysical probes (Miller et al., 1998). This aircraft has excellent equipment on board to help monitor its performance in icing conditions. Photographs of the ice accretions on the aircraft help provide useful data. The main function of the Twin Otter was to fly over the Mirabel site into icing conditions, in a similar manner to the Convair-580.

C-130: The NSF/NCAR C-130 flew with its standard cloud microphysical package, which included a SPEC HPVS system. The DRI Large and Standard Cloudscopes, and the DRI Large T-Probe (Hallett et al., 2005) were also installed for cloud microphysical measurements. Remote sensing capabilities centered on the SABL Scanning Aerosol Backscatter Lidar. However, a major emphasis for the instrumentation was on the measurement of aerosols and their properties. Besides a PMS PCASO/SPP probe and a TSI CN Counter, a DRI CCN Spectrometer, a Colorado State University Continuous Flow Diffusion Chamber Ice Nuclei Counter, a CSIRO Giant Nuclei Impactor, and an NCAR Counter Flow Virtual Impactor Droplet Residual Nuclei Analyzer were installed. The main purpose of the C-130 was to understand the formation of large droplets and the initiation of ice in the atmosphere. It tended to fly upstream of Mirabel in air that was forecast to arrive over the site.

Citation: The University of North Dakota Citation was instrumented with standard cloud microphysical instrumentation and had a dropsonde system onboard. Its main mission was to fly underneath the NASA ER-2, while it was flying near and over Mirabel to help provide data to compare with the ER-2 remote sensors.

ER-2: The NASA ER-2 flew at high altitudes (approx. 50,000 ft) and it mainly had a remote sensing role for AIRS II. Its payload included a MODIS Airborne Simulator (MAS), the Scanning High-resolution Interferometer Sounder (S-HIS), the NPOESS Atmospheric Sounder Testbed – Interfermometer (NAST-1), the Microwave Temperature Sounder (NAST-MTS), the Cloud Physics Lidar (CPL) and a fast in-situ ozone sensor.

III. Summary of Operations

The project was conducted between 3 November 2003 to 13 February 2004 and had two intensive operating periods (IOPs): 4 November to 12 December (IOP1) and 19 January to 13 February (IOP2). Some of the basic ground instrumentation was run throughout the whole period including the time between IOPs. Most of the U.S. based organizations only participated during IOP 1. The Convair-580 was the only aircraft operating during IOP2. A summary of data collected at Mirabel during both IOPs is given in Fig. 1. It can be seen that during IOP1, on several occasions, coordinated flights with several aircraft were made over the airport.

A summary of the types of icing conditions encountered by each aircraft during the project is given in Table 3. The Convair-580 encountered more severe and more frequent icing episodes than the other aircraft. However, it was flown during both IOPs and thus had more opportunities. The C-130 tended to avoid icing encounters, at least those where the icing might be considered more than light, because the inlet tubes for the aerosol instrumentation tended to ice up during such events. The Citation and ER-2 operations were split between AIRS2 and the THORPEX project (reference) and were only operating during a portion of IOP1. This severely restricted their ability to get into icing conditions. Not all of the icing encounters were over Mirabel because the aircraft were flown into forecast regions of icing if suitable conditions did not occur over Mirabel.

IV. Weather Forecasting

Weather forecast support for AIRS-II operations was provided by operational forecasters from Environment Canada and researchers from the National Center for Atmospheric Research and Meteo-France. This collaboration brought together unique approaches to the problem of diagnosing and forecasting icing conditions. Operational forecasters from Canada provided critical expertise on regional phenomena and synoptic-scale storm development, while researcher experience with icing flight programs was used to hone the forecasts down to microphysical

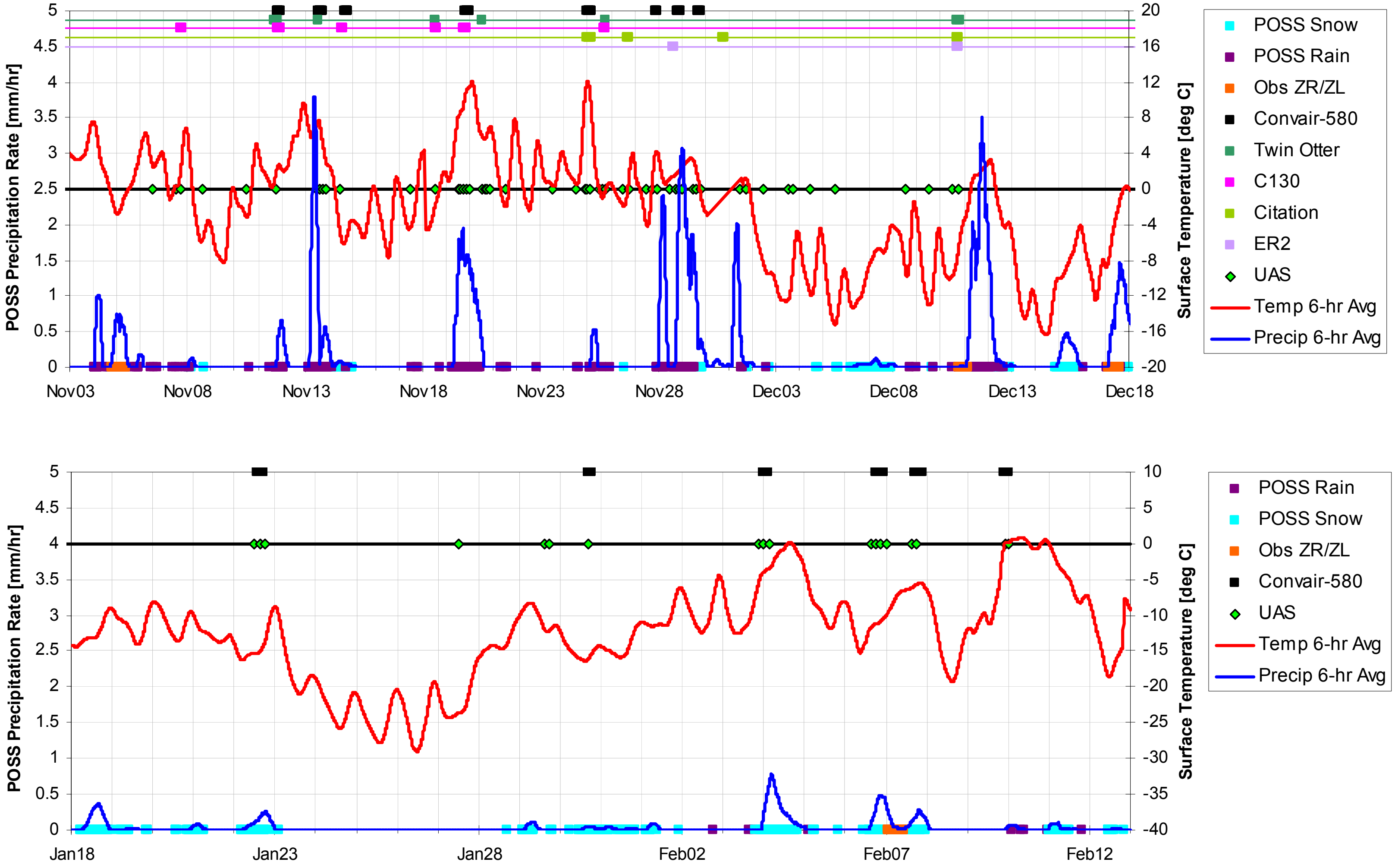

Figure 1. Time history at Mirabel during IOP1 and IOP2 of precipitation rate, as determined using the POSS, and surface temperature, both calculated using a 6 hour running average. The times the various aircraft were over Mirabel are indicated, along with the times of the upper air soundings (UAS) made at the site. The periods when snow, rain and freezing rain were observed at the site are indicated.

	Number of	Maximum Icing Intensity		
	Flights	Severe	Moderate	Light
Convair-580	22	5	6	9
Twin Otter[1]	18	1	1	3
C-130[2]	15	0	4	8
Citation[3]	18	0	2	2
ER-2[3]	9	Flights were above icing		

[1] Some Twin Otter flights were ferry flights.

[2] Many C-130 flights were made out of the Mirabel area

[3] Many Citation and ER-2 flights were for THORPEX

Table 3. Summary of icing conditions encountered by aircraft

aspects that were of specific interest to the program. Forecasters made use of standard forecast methods, in combination with experimental icing tools and state-of-the art instrumentation based at Mirabel. Experimental tools available to forecasters included real time observations from a radiometer, balloon-borne soundings, imagery from the vertically pointing McGill radar, derived satellite fields and model output from the GEM, HIMAP, RUC and MM5.

AIRS-II provided several challenging forecast problems. Of greatest interest to the program, was the prediction of the presence, amount and drop size associated with supercooled liquid water events over and in the vicinity of Mirabel. Glaciated, mixed-phase and above-freezing conditions were also of interest. Short-range (0-6 hour) forecasts of these phenomena were supplied each morning to plan flight and ground-based operations for the day. Expected timing of the conditions was most critical, because aircraft had to be staged appropriately to sample the environment. Some aircraft needed several hours notice to be in place, and several had limited on-station times. Ceiling, visibility, precipitation and wind forecasts were necessary to provide reliable alternates for the aircraft. Escape routes were also identified to supply pilots with a safety margin if the aircraft became heavily iced.

Long-range forecasts were needed for project planning, but also for a critical aspect of the NCAR C-130 operations. Researchers hoped to sample the pre-cloud, airmasses upstream of non-classical SLD icing events to measure the concentrations of cloud condensation nuclei, ice nuclei and ultra-giant nuclei. Backward trajectory model runs were used to estimate upstream 3-D location of the airmasses that were expected to be found over Mirabel for the next day. A “re-analysis” example is given in Fig. 2 for 11 November 2003. This process required fairly precise 24+ hour forecasts of the potential for, timing and altitude of SLD, because slight changes in the timing, location or altitude of the SLD icing could result in vastly different back trajectory locations. Since non-classical SLD is difficult to forecast in the short-term (0-3 hours), forecasters were limited to providing rough estimates of the 24+ hour SLD potential and locations.

V. Case Studies

In order to illustrate the types of data collected during AIRS II, several case studies have been selected. They include 11, 19, and 25 November 2003 and 6 February 2004. For all these cases, moderate or severe icing was reported by the Convair-580 scientists flying over Mirabel.

A. 11 November 2003 Case Study

On 11 November 2003, forecasters expected glaciated conditions above the freezing level during the morning, with a transition to water dominated clouds with some potential for SLD icing between 2 and 6 km MSL starting after ~1700 UTC and lasting for up to 8 hours. The icing clouds were expected to form ahead of an advancing warm front, in a stably-stratified environment. The event was forecast a day in advance, allowing the NCAR C-130 to sample the expected upstream air masses over Lake Michigan on 10 November. Short-range forecasts indicated that glaciated conditions, with an outside chance for pockets of icing, were expected over Mirabel in advance of the main icing event.

During the icing event, the Current Icing Potential (CIP) algorithm (Bernstein et al., 2005) indicated a high potential for icing between 1.5 and 4.0 km with lower potentials up to 6.0 km (Fig. 3). SLD potential was determined to be “unknown” through 22:00 UTC because the Rapid Update Cycle model moisture profile used by CIP did not include any indication of the presence of the dry intrusion that was so important in the case. SLD was indicated over Mirabel at later times.

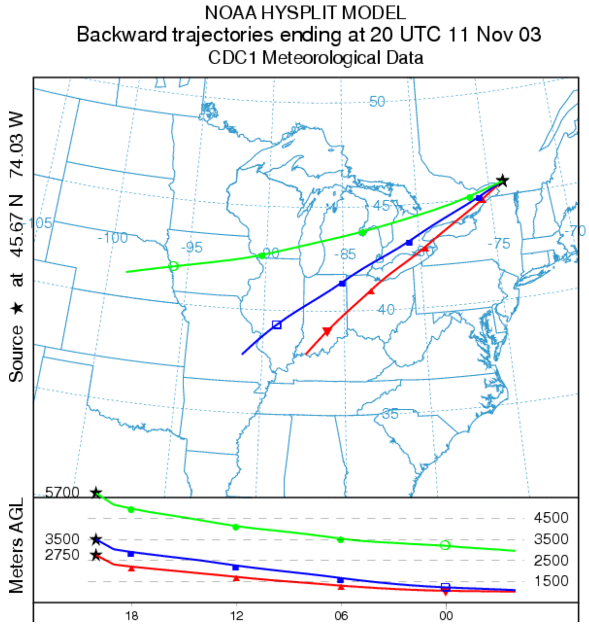

Figure 2. Backward Trajectory for a 24 hour period performed using the re-analysis data for 11 November 2003

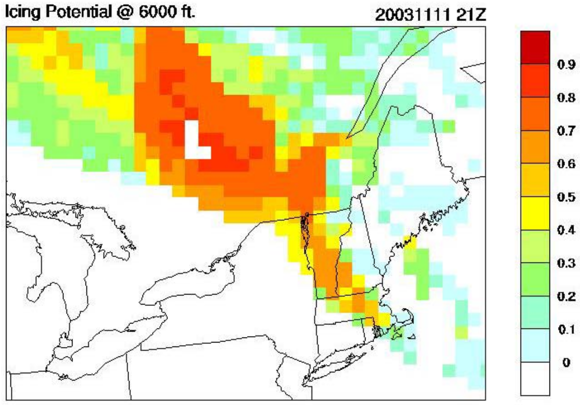

Figure 3: The Current Icing Potential (CIP) algorithm for 21 UTC on 11 November 2003.

The clouds evolved roughly as forecast on 11 November. During its first flight over Mirabel between 1630 and 1745 UTC, the Twin Otter found that the clouds above the freezing level were dominated by snow, including hexagonal plates, irregular and aggregate crystals, with very little, if any, supercooled liquid water. Rain was found beneath the bright band. Cloud top heights observed from GOES-12 at that time ranged between 8 and 10 km. A mid-level dry intrusion moved eastward from Michigan and Georgian Bay, reaching the project area somewhat later than expected, at ~20:00 UTC. The single, deep, glaciated cloud layer was broken into two distinct layers, with the lower, icing layer limited to below ~2-4 km MSL. The Twin Otter departed Montreal's Dorval airport, southeast of Mirabel at 19:18 UTC, then flew several vertical profiles over Mirabel over the two hours that followed. During the initial climb, rain was observed from the surface to the freezing level at ~1.4 km, with ice crystals above, and some mixed-phase, light icing in a brief patch near 3.9 km. The initial descent over Mirabel was made at 19:45 UTC in a mixed phase environment that featured individual and aggregated columnar crystals, as well as liquid water contents (LWC) of 0.1-0.25 gm^{-3}. After completing a missed approach at 20:09 UTC, the aircraft climbed to find that conditions had changed to become dominated by supercooled drizzle with LWC of up to ~0.5 gm^{-3} at a static temperature of -1.5°C and an altitude of 2.3 km. Drop diameters exceeding 600 µm were observed and the pilots reported that ice accreted aft of the ice protection system, with a small ridge of ice at the trailing edge of the boot. A pilot report of moderate-to-severe clear icing was made. Icing conditions in this altitude range and in pockets at altitudes as high as 3.7 km were sampled by the NRC Convair-580 and the NCAR C-130.

Figure 4 shows the Convair-580 liquid and ice water contents measurements (from 1 s data) as a function of altitude over Mirabel when the aircraft was within 10 km of Mirabel (45.68N, 74.01W). The fraction of PMS 2D imagery at sizes greater than 100 µm that were classified as spherical (Korolev and Sussman, 2000) is also shown. The averaged HIMAP model, McGill Vertical Pointing Radar and the CRC WV/TP-3000 profiling radiometer liquid water contents are also shown in a separate panel along with the model and radiometer estimates of the freezing level. The McGill VPR data were obtained using the technique of Zawadzki et al. (2000). Above the freezing level near 0.8 km, a significant fraction of the large particles were spherical indicating the presence of supercooled large drops and drizzle. The pilots reported that the Convair-580 encountered light to moderate icing during this event.

It was raining at the surface during this event and this creates potential problems for the radiometers. The CRC WV/TP-3000 had a special blower and water repellant window installed which kept the window fairly clear of standing water, helping to decrease at least one aspect of the rain problem. However, the temperature sounding looks unreasonably warm in comparison to the balloon, model and aircraft soundings, and the “measured” liquid water contents were unrealistically high, reaching values over 1 $g\ m^{-3}$, or well above what was measured with the aircraft sensors. Both the HIMAP model and the VPR were predicting liquid water above the site, but the profiles of liquid water do not seem to match the aircraft data.

Figure 5a shows the GRIDS Ka-band polarization radar data which detected a pocket of supercooled large drops between 20:10 to 20:18 UTC that was verified during in-situ aircraft data. The depolarization ratio (DR: slant-45 linear polarization basis) is an accurate means of detecting the presence of ice: values near +30 dB are an indication of spherical water droplets whereas values below ~ 28 dB denote the presence of ice. [Note that DR values are typically presented on an inverted scale such that spheres are -30 dB in this radar; however in this case the real-time software that produced this image inverted the scale.] In Figure 5b the GRIDS’ icing hazard product is presented. The GRIDS algorithm incorporates RUC temperature profiles, radar reflectivity and depolarization ratio measurements and microwave radiometer estimates of total columnar liquid to determine the presence of absence of supercooled liquid. This product captured the formation of the pocket of SLD between 20:14 to 20:18 UTC, which persisted until ~20:45 UTC. Schneider et al. (2005) discuss this case in more detail.

Figure 6 shows the lidar time history for the extinction coefficient, the particle mixing ratio, the effective particle diameter and the depolarization ratio (see Bissonnette et al., 2002, 2003). The lidar solutions show a descending small-particle cloud layer from an altitude of 1.3 km at 19:00 to 400 m at 22:30 UTC. The layer is about 150-200 m deep, of moderate extinction (1-15/km), with median particle diameters (20-80 µm) and small depolarization ratio (<5% or spherical water droplet) at least beyond 22:30 UTC where the layer falls below 1000 m. Above this layer, the depolarization is relatively high, up to 40%, indicating the presence of ice. For the range-time region between 750 m and 1100 m in altitude, and 21:25 and 22:25 in time, the particle volume mixing ratio is particularly high there, up to 0.4 cm^3/m^3, and highly structured. This is in good agreement with the Nevzorov LWC profile that show values reaching 0.3-0.4 gm^{-3} at 1000-1200 m and wide fluctuations at the constant-altitude transects. The indicated particle size for that region is large, 150-600 µm, and so is the depolarization ratio, 30-40%, indicating the presence of crystals. The depolarization ratio thus indicates at least mixed phase, which is consistent with the 2D sphere fraction varying between 0 and 75%.

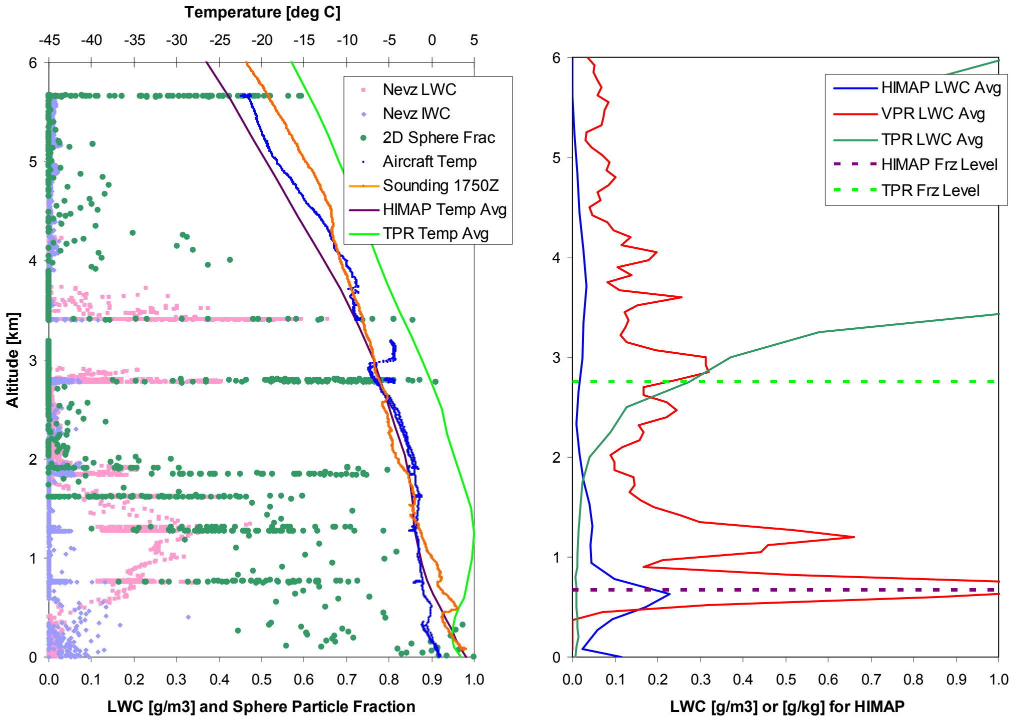

Figure 4. Profiles above the Mirabel site for 11 November 2003, 1940-2210 UTC, showing the aircraft data on the left panel along with the temperature profiles from the rawindsonde, HIMAP model, and the profiling radiometer. The right panel shows the liquid water profiles for the model, radar and radiometer averaged over the time period, along with the model and radiometer estimates of the freezing level.

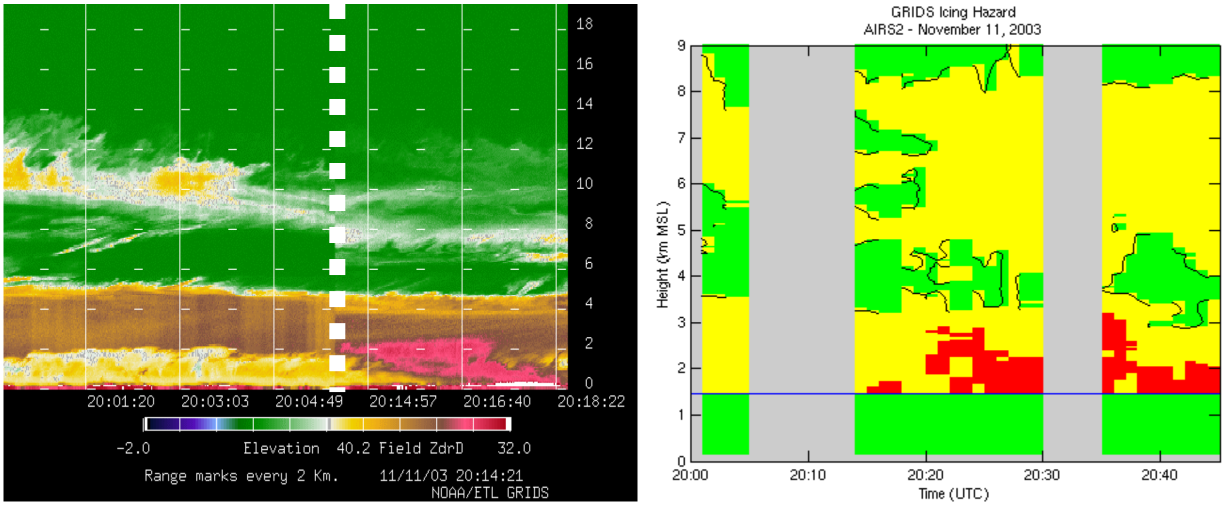

Figure 5. (a, left) Example of the GRIDS radar imagery showing a pocket of supercooled large drops in red (near 20:16 UTC that was detected and verified with in-situ aircraft data. The yellow and orange colours indicate the presence of ice crystals. (b, right) Time-height image of the GRIDS' icing hazard. Green=safe; yellow=caution; red=definitive hazard. The blue horizontal line indicates the freezing level determined from the RUC model. The vertical grey bars are periods where the radar was scanning

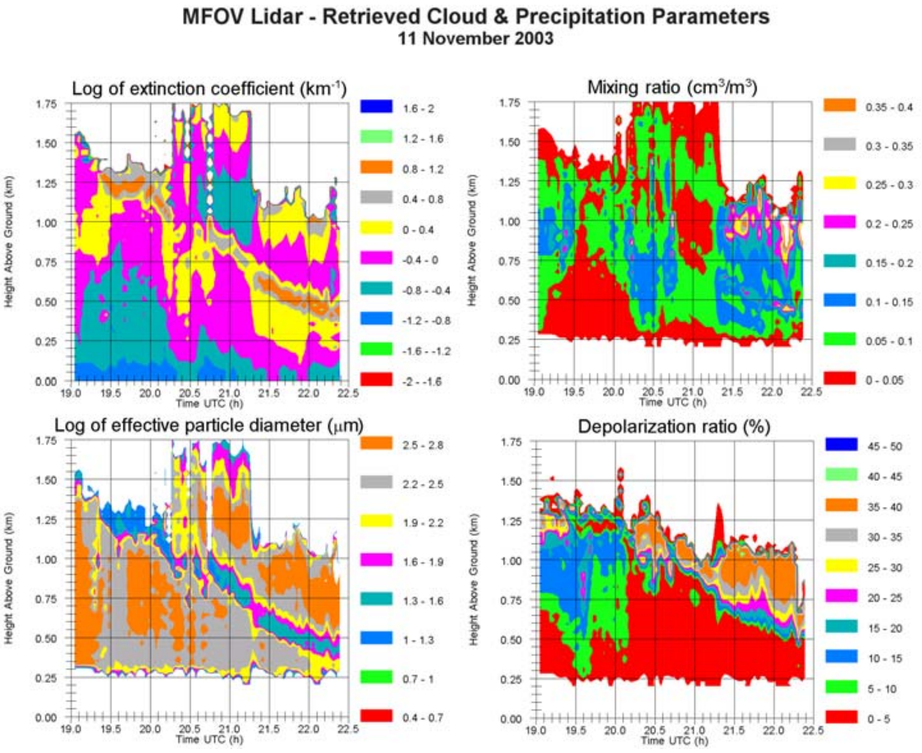

Figure 6. DRDC lidar imagery for 11 November 2003 showing extinction coefficient, mixing ratio, effective particle diameter and depolarization ratio.

B. 19 November 2003 Case Study

Figure 7 shows the Convair-580, VPR, rawindsonde, HIMAP and CRC radiometer data over Mirabel in a similar manner as was described for Fig. 4. Once again there was rain at the surface and the radiometer temperature profile looks too warm, and the radiometer liquid water estimates are unrealistically high. The radiometric data looked very suspicious around 22:30 UTC so the averages are limited to the period before that time. The PMS 2D analysis shows most of the larger particles are spherical below the freezing level, as expected. Above the freezing level, it appears that most of the liquid water was in the form of small droplets. The HIMAP and VPR liquid water profiles show that some supercooled liquid water was detected, although in the case of HIMAP, the values are quite low. The Convair-580 pilots reported moderate and perhaps severe icing during this episode.

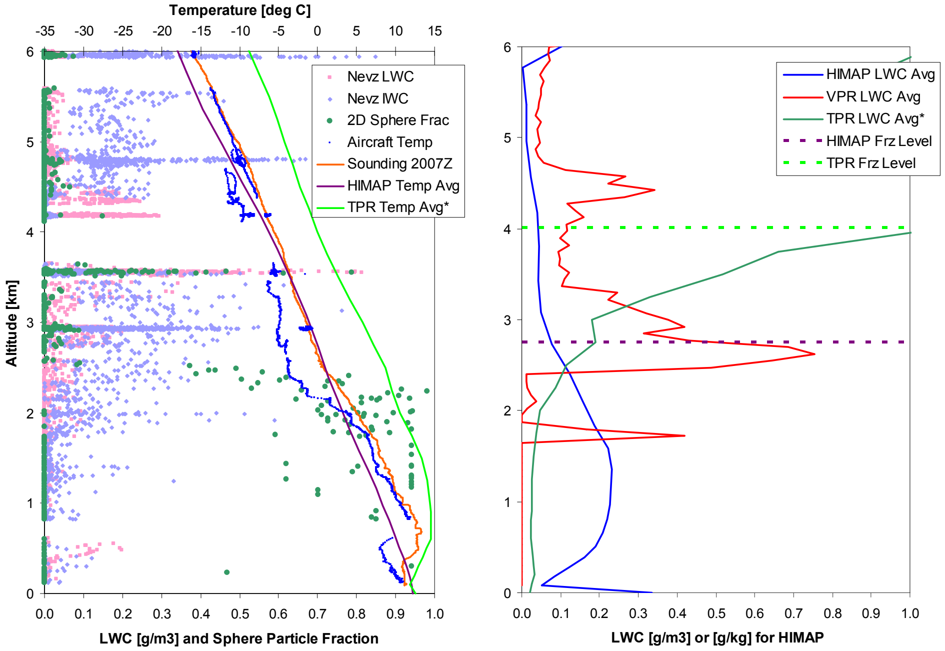

Figure 7. As in Fig. 4 but for 19 November 2003, 2045-2345 UTC (*2045-2230 UTC for WV/TP-3000).

C. 25 November 2003 Case Study

Figure 8 shows the Convair-580, VPR, rawindsonde, HIMAP and CRC radiometer data over Mirabel in a similar manner as was described for Fig. 4 but for 25 November 2003. In this case, although rain was reaching the ground, the microwave radiometer values look quite reasonable when compared with the aircraft data and the VPR data. The VPR suggests a large amount of supercooled liquid near the surface which was not observed by the aircraft since it never went below 900 m. Most of the liquid water was in small drops for this case, and the pilots reported light to moderate icing.

Figure 9 shows data from the University of Wyoming (WCR) radar installed on the Convair-580 during IOP1 for this case. The WCR installation on the Convair-580 and summary of the radar icing measurements are given in Wolde et al. (2005). During the time segment shown in the images the aircraft descended from 2.7 km (0°C) to an altitude of 2.5 km (–4°C). The main features in the images are:

- Prior to ~02:10 UTC: High LWC with fine-scale LWC variability that matches the horizontal Z changes at the 2nd radar range gate (in this case 105 m).
- A sharp Z gradient as the aircraft enters from high LWC icing region into ice clouds (02:10-02:12). In this segment the LWC dropped from near 1 to 0.2 while the Z increased from ~-10 dBZ to ~20 dBZ.
- Systematic Z and LWC variability suggesting wave activity
- Melting layer: well defined and slightly at lower altitude in the glaciated segment cross-section.

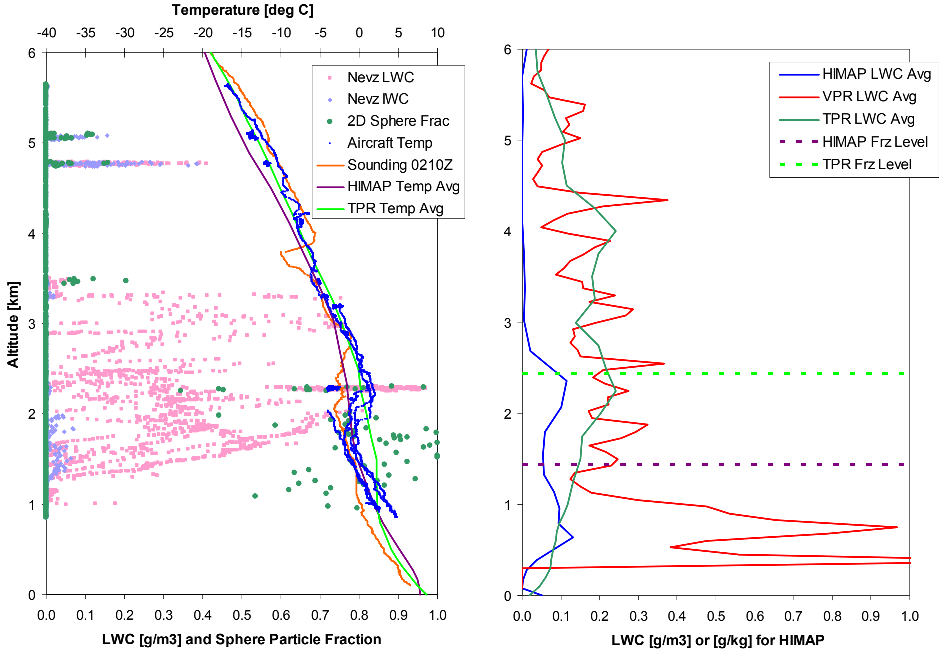

Figure 8. As in Fig. 4 but for 25 November 2003, 0025-0345 UTC

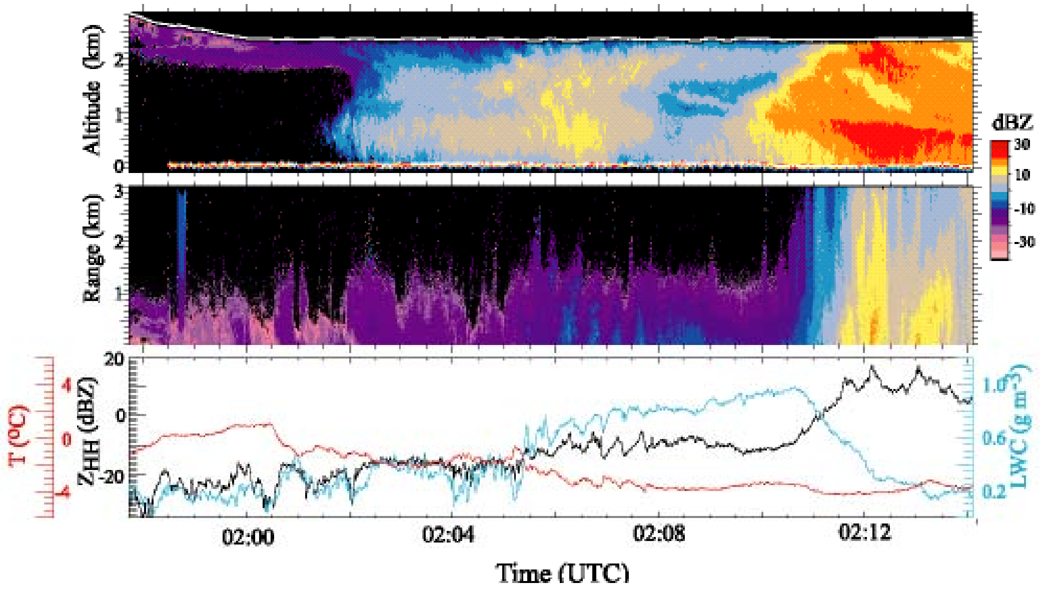

Figure 9. Vertical (top panel) and horizontal (middle panel) cross-section of radar reflectivity measured by the Wyoming 95 GHz cloud radar on November 25, 2003. The bottom panel shows time series of radar reflectivity (Z_{HH}) at 105 m horizontal distance from the aircraft and LWC measured by the King probe and corresponding temperature (T).

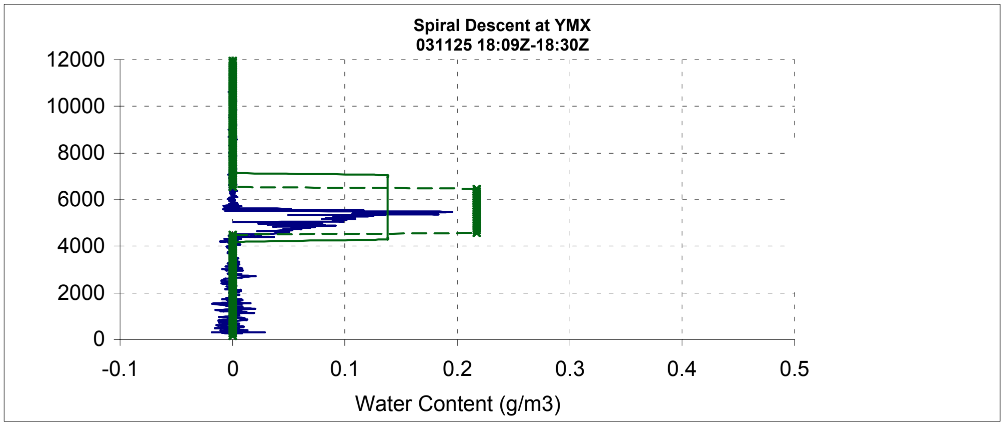

Figure 10. An example of an NIRSS product for 25 November 2003 comparing flight measured (blue) to remotely sensed liquid water content (green).

Figure 10 shows the results from a first generation NASA Icing Remote Sensing System post-processing software that is used to detect supercooled liquid water zones (Reehorst et al., 2005). It uses an X-band radar and the ceilometer to define the cloud boundary. It uses the profiling radiometer to determine the temperature profile and liquid water path. It then distributes this liquid water content uniformly over the cloud region. Using a supercooled liquid water threshold of 0.1 g m^{-3}, the algorithm predicted light rime icing for this time period on 25 November.

In this highly variable environment, CIP indicated intermittent periods of moderate icing potential (0.6), mostly between 3 and 4km MSL, with some very low (0.01-0.10) values from 4km to 7km at times. Small pockets of moderate SLD potential were occasionally indicated near Mirabel. Cloud top temperatures were highly variable and were as warm as -5^{o}C at times. RUC model temperature forecasts had the freezing level just below 3km, and there was no icing potential indicated from that level down to the surface. Figure 11 shows a sample CIP product for this day.

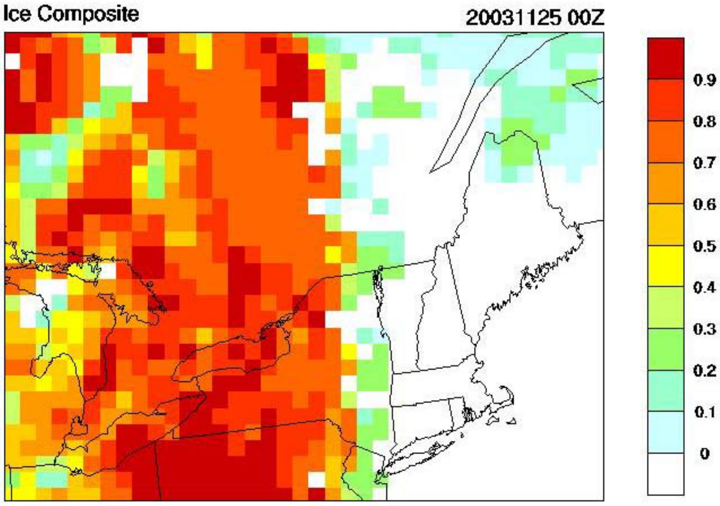

Figure 11. A CIP product for 25 November at 21 UTC.

D. 6 February 2003 Case Study

Figure 12 shows the Convair-580, VPR, rawindsonde, HIMAP and CRC radiometer data over Mirabel in a similar manner as was described for Figure 3 but for 6 February 2003. Here the surface temperature was below freezing and snow was falling. The temperature profiles from all the different techniques agree reasonably well. The liquid water content profiles from the aircraft, HIMAP model, VPR, and WV/TP-3000 agree reasonably well for this case. During this event, the Convair-580 pilots reported moderate to severe icing over Mirabel.

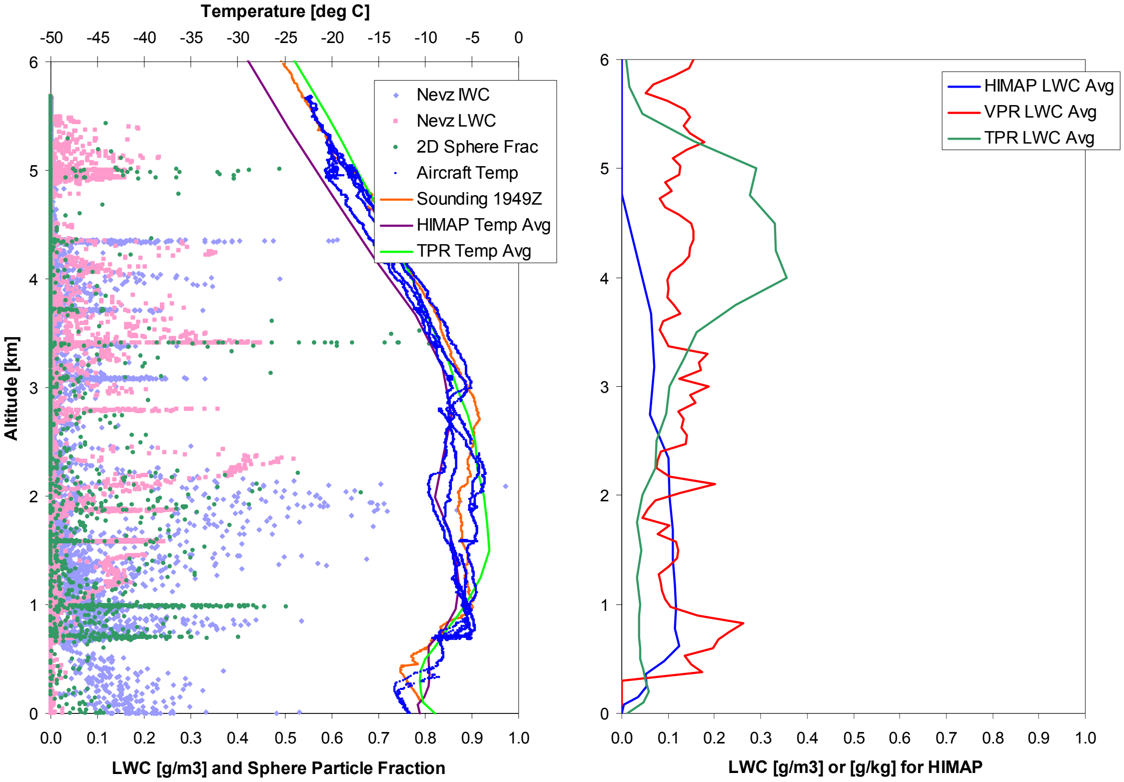

Figure 12. As in Fig. 4 but for 6 February 2004 1900-2210 UTC.

VI. Satellite Detection Systems

Satellite data provides a very powerful tool to detect and forecast icing conditions, representing however, only cloud tops, when the clouds are optically thick. Many of the AIRS II forecast systems are designed to use algorithms which can detect the presence of supercooled drops and retrieve the phase, and size of the droplets, and liquid water path (LWP) from the satellite data alone. These include a near real-time cloud and icing analysis based on the visible infrared solar-infrared split-window technique (VISST, Minnis et al. 1995) that is applied to GOES data (Minnis et al. 2004). Figure 13 shows an example of one such forecast for 24 November where a liquid phase region identified as an icing band was determined from various criteria related to satellite temperature and reflectance measurements. On this particular day near the time of the figure, the Convair-580 encountered severe icing in a shallow stratocumulus deck related to a cold front north of Lake Huron and Georgian Bay. Near the same time, the Citation flying over Lake Ontario encountered light or no icing conditions. These observations are in agreement with the diagnosis using the satellite data.

The area of icing seen in Fig. 13 moved over the Mirabel area during 25 November. The NASA Glenn Twin Otter flew an icing pattern southwest of the airport between 17:15 and 19:45 UTC. The cloud phase detected with the VISST at 18:15 UTC is shown in Fig. 14 with an overlay of the entire flight track. The corresponding LWP field shows that the LWP ranged between 50 and 250 gm^{-2} over the flight leg. The satellite results taken each half hour were matched closely in time and space with the aircraft. The resulting cloud base and top heights derived from the GOES-12 data are plotted along with the Rosemount icing results at the aircraft flight altitude at the bottom of Fig. 14. The satellite results indicate mostly medium probability of icing over the entire flight track while the aircraft shows on and off icing during the flight. The satellite cloud base height appears to coincide with the absence of icing when the aircraft is low, but the VISST cloud-top altitude might be overestimated.

The surface data are also valuable for assessing the satellite icing parameters. For example, Fig. 15 shows a preliminary scatter plot of LWP from the Mirabel microwave radiometer and the VISST retrievals. Although the results are highly correlated and show a small average difference, the differences at the upper and lower ends of the range will require further analysis. Additional detailed studies validating the icing diagnoses from satellite observations are currently in progress.

On many occasions, icing in lower layer clouds was obscured by an upper cloud layer. This was the case for much of the 11 November and 6 February cases and for all of the 19 and 24 November cases discussed above. This inability to "see" through the upper level clouds suggests that satellite data will need to be augmented with other data when used as an operational tool to predict icing conditions.

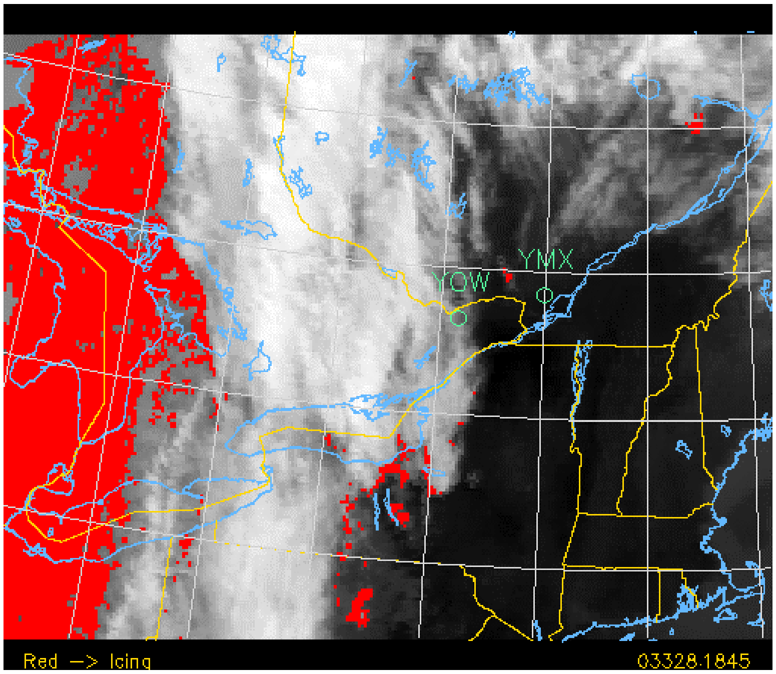

Figure 13. GOES satellite derived icing detection scheme for 24 November 2003. The icing regions are shown with a red-color overlaid on an IR image where the ice phase is indicated with a whitish color. The dark-black areas represent the Earth's surface. Within the icing detection algorithm, the range of IR temperatures where icing might occur is assumed to be 0^{o}C to -25^{o}C.

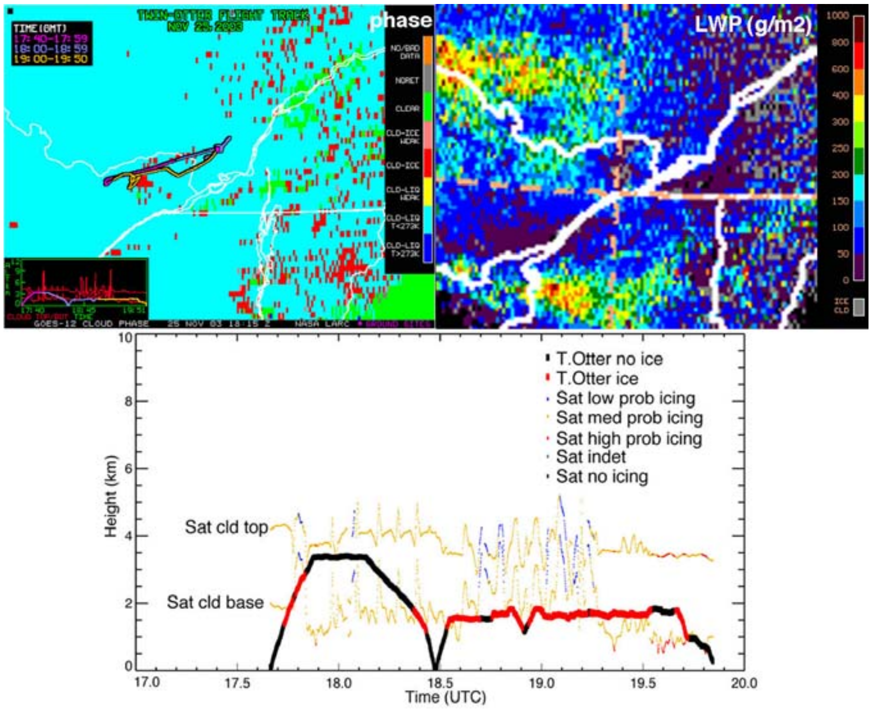

Figure 14. Cloud properties derived from GOES-12 data over southern Quebec and Ontario at 18:15 UTC, 25 November 2003. Upper left panel, Twin Otter flight track overlaid on the phase image that shows most of the area is covered by supercooled liquid water clouds (light blue); upper right panel, LWP from VISST; bottom, matched cloud boundaries and icing probability from GOES overlaid with Twin Otter icing and altitude.

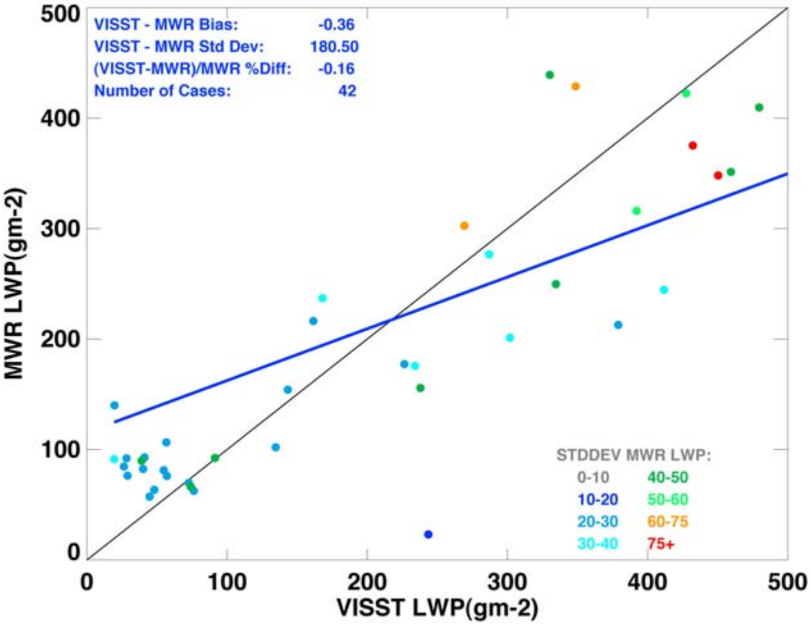

Figure 15. Comparison of LWP from Mirabel microwave radiometer and GOES-12 VISST retrieval for November and December 2003.

VII. Model/Radiometer Comparison

Figure 16 shows a comparison of the HIMAP model and the CRC Profiling Radiometer liquid water path and water vapour path above the Mirabel site when there was no precipitation or fog reported which might have affected the radiometer readings. The data still needs to be fully quality controlled but the water vapour path comparison shows reasonable agreement. However, there appears to be no correlation with liquid water path. The lack of agreement might be due to either radiometer problems in detecting liquid or the model's inablility to predict cloud water. Guan et al. (2002) compared the model predictions with aircraft observations and showed the model had difficulty predicting liquid water contents. It was also shown above that the radiometer had some problems as well (e.g. Figs. 4 and 7). Sheppard et al. (1991) performed a comparison of the radiometer measurements with aircraft soundings and such a study should be performed using AIRS II data. It should be mentioned that during the project both the model and the radiometer liquid water path were providing very useful information for directing aircraft into icing zones. So the impression given by Fig. 16 might be overly negative.

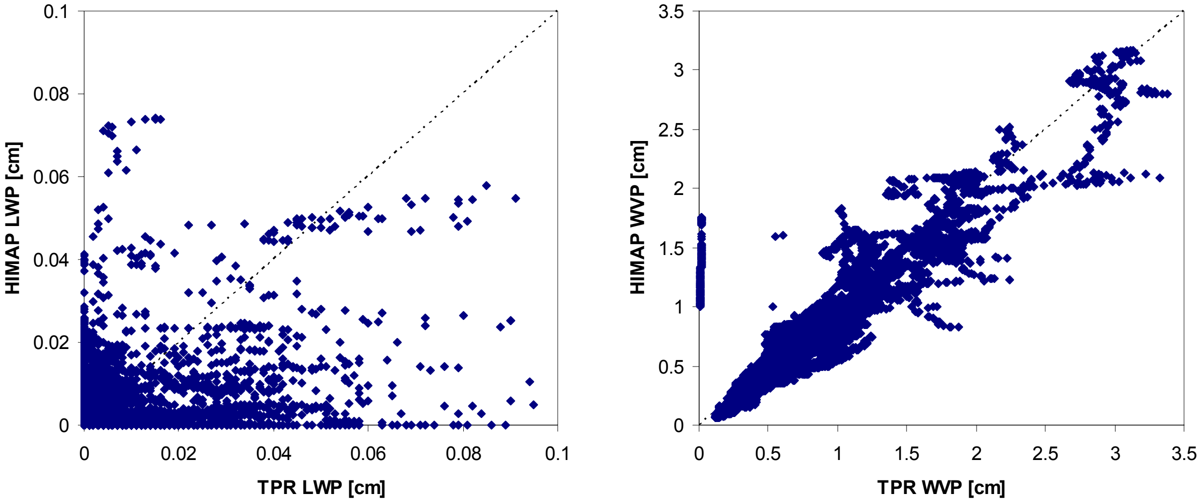

Figure 16. A comparison of HIMAP Model and Profiling Radiometer liquid water and water vapour path.

VIII. Precipitation Sensor Comparison

Figure 17 shows a comparison of the DRI/NCAR designed hot plate (Rasmussen et al., 2002) and the POSS (Sheppard, 1990) precipitation rates as measured at Mirabel. Six minute intervals are used for the comparison. It should be noted that the hot plates do not register anything below 0.3 mm hr^{-1}. For any airport use, the standard gauges that normally produce precipitation rates on a coarse time resolution (hours) are not adequate The POSS has been shown to be a useful instrument for measuring rainfall rates and for detection and typing of precipitation during winter (Sheppard and Joe, 1994 and 2000). It detects the fall speed of the precipitation particles and for rain, it is easy to convert this into precipitation rates using standard fall speed versus drop size relationships. However, for snow, no such relationship exists and the sensor must use a radar reflectivity versus precipitation rate relationship which is not as precise. Ice particle density can vary over a wide range and this leads to uncertainties in precipitation rates. The hot plate is a relatively new instrument which measures the amount of heat required to evaporate or sublimate the precipitation falling onto the sensor. This heat flux can then be converted into a precipitation rate. However, assumptions are also needed for this instrument, especially in high wind speeds where turbulence can lead to some uncertainties. The current measurements have shown significant variability of precipitation rates over times scales near one minute. This could also lead to some substantial scatter as shown in Figure 17. All available sensors have some weaknesses. However, both these sensors show great promise for making measurements. To be confident of making accurate precipitation measurements on a fine time scale, such as minutes, further work needs to be performed.

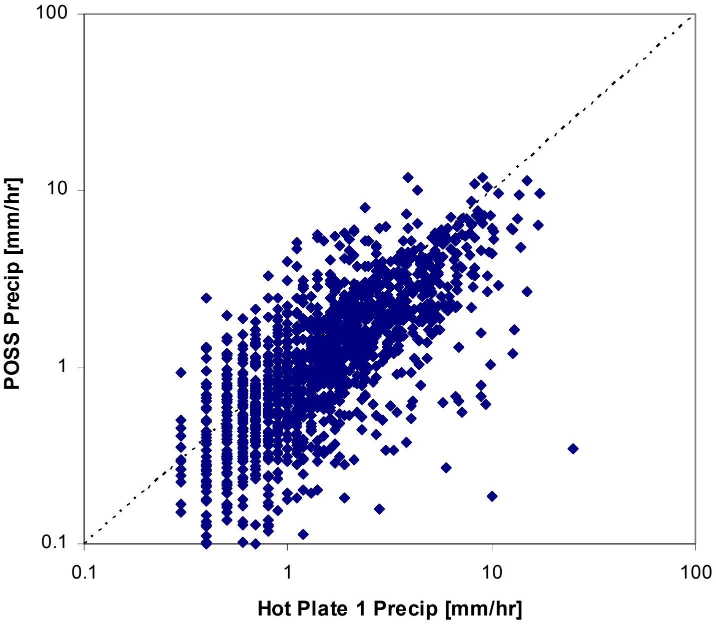

Figure 17. A comparison of the DRI/NCAR hot plate and POSS precipitation measurements.

VIII. Summary

AIRS II provided an excellent data set to help develop and tune various forecast systems such as CIP, FIP, AVISA, NIRSS and GRIDS. This paper shows that many individual components that might be used for these systems have problems. As indicated more work is need to better interpret model, radar, radiometer and precipitation data. The forecast systems should work better by collecting data from many different sources, and determining a forecast knowing the limitations and strengths of each component. However, the ability of a human to interpret the data and correctly assess whether icing was likely over Mirabel at that time or in the near future was very impressive. The challenge is to produce an automated system that can duplicate the ability of a person to make useful decisions from a wide range of input parameters.

This paper concentrated on results related to the operational type objectives for AIRS II. However, there were many studies designed to help us better understand the physical processes whereby supercooled large droplets form and clouds go from being all supercooled water to glaciated clouds. Other studies were designed to help us better understand aircraft performance in icing conditions. In addition, the certification authorities wanted more data to help characterize the icing environment, especially in large droplet conditions. A significant amount of data was collected towards these objectives and will be described in other papers.

Acknowledgments

Besides our own organizations, the authors wish to acknowledge the help and sponsorship of the following institutions within Canada and the U.S. For Canada, Transport Canada, the National Search and Rescue Secretariat, the Canadian Foundation for Climate and Atmospheric Sciences, the Natural Sciences and Engineering Research Council, and the Communication Research Centre contributed. For the U.S. the efforts and support of the Federal Aviation Administration and the National Science Foundation must be acknowledged. Thanks to Cory Wolff of NCAR for regenerating CIP output for the cases described in this paper.

References

Bernstein, B.C., F. McDonough, M.K. Politovich, B.G. Brown, T.P. Ratvasky, D.R. Miller, C.A. Wolff and G. Cunning, 2005: Current Icing Potential (CIP): Algorithm Description and Comparison with Aircraft Observations. J. Appl. Meteor, in press.

Bissonnette, L.R., G. Roy, L. Poutier, S.G. Cober, and G.A. Isaac, 2002: Multiple-scattering lidar retrieval method: tests on Monte Carlo simulations and comparisons with in situ measurements. Appl. Opt., Vol. 41, 6307-6324 .

Bissonnette, L.R., G. Roy, and N. Roy, 2003: Ground-based lidar measurement of liquid water content and effective droplet diameter in water clouds: instrumentation, retrieval methods and results. SPIE Conference Proceedings, Vol. 5235, 537-548.

Brown, A., 2005: Preliminary Correlation of AIRS In-flight Icing Lift/Drag Degradations with Icing Environmental Conditions. AIAA 43rd Aerospace Sciences Meeting and Exhibit, Reno, NV, January 10-13, 2005, Paper AIAA-2005-1067

Cober, S.G., Isaac, G.A. and J.W. Strapp, 2001: Characterization of aircraft icing environment that include supercooled large drops. *J. Appl. Meteor.*, **40**, 1984-2002

Guan, H., S.G. Cober, G.A. Isaac, A. Tremblay and A. Methot, 2002: Comparison of three cloud forecast schemes with in-situ aircraft measurements. *Wea. Forecasting*, **17**, 1226-1235.

Hallett, J., R. Purcell, M. Roberts, G. Vidaurre§,and D. Wermers, 2005: Measurement for characterization of mixed phase clouds. AIAA 43rd Aerospace Sciences Meeting and Exhibit, Reno, NV, January 10-13, 2005, Paper AIAA-2005-0862.

Isaac, G.A., S.G. Cober, J.W. Strapp, D. Hudak, T.P. Ratvasky, D.L. Marcotte, and F. Fabry 2001a: Preliminary results from the Alliance Icing Research Study (AIRS). *AIAA 39th Aerospace Sci. Meeting and Exhibit*, Reno Nevada, 8-11 January 2001, AIAA 2001-0393.

Isaac, G.A., S.G. Cober, J.W. Strapp, A.V. Korolev, A. Tremblay, and D.L. Marcotte, 2001b: Recent Canadian research on aircraft in-flight icing. *Canadian Aeronautics and Space Journal*, **47**, 213-221.

Knollenberg, R. G. 1981: Techniques for probing cloud microstructure. In: *Clouds, their formation, Optical properties, and Effects*, P. V Hobbs, A..Deepak, Eds.Academic Press, 495 pp.

Korolev, A. and Sussman, B. 2000: A technique for habit classification of cloud particles. *J. Atmos. Oceanic Technol.* **17**, 1048–1057.

Miller, D., T. Ratvasky, B. Bernstein, F. McDonough, and J.W. Strapp, 1998: NASA/FAA/NCAR Supercooled Large Droplet Icing Flight Research: Summary of Winter 96-97 Flight Operations. 36th Aerospace Science Meeting and Exhibit, Reno, NV, 12-15 January. American Institute of Aeronautics and Astronautics, Washington, D.C.

Minnis, P., D. P. Kratz, J. A. Coakley, Jr., M. D. King, D. Garber, P. Heck, S. Mayor, D. F. Young, and R. Arduini, 1995: Cloud Optical Property Retrieval (Subsystem 4.3). "Clouds and the Earth's Radiant Energy System (CERES) Algorithm Theoretical Basis Document, Volume III: Cloud Analyses and Radiance Inversions (Subsystem 4)", *NASA RP 1376 Vol. 3*, edited by CERES Science Team, pp. 135-176.

Minnis, P., W. L. Smith, Jr., L. Nguyen, D. A. Spangenberg, P. W. Heck, R. Palikonda, J. K. Ayers, C. Wolff, and J. J. Murray, 2004: Near-real time cloud properties and aircraft icing indices from GEO and LEO satellites. *Proc. SPIE 49th Ann. Mtg., Earth Observing Systems IX Conf.*, Denver, CO, August 2-6.

Rasmussen, R.M.,J. Hallett, R. Purcell, J. Cole, and M. Tryhane, 2002: The hot plate snowgauge 11th AMS Conference on Cloud Physics, 3-7 June 2002, P1.6.

Reehorst, A.L., D.J. Brinker and T. Ratvasky, 2005: NASA Icing Remote Sensing System comparisons from AIRS II. AIAA 43rd Aerospace Sciences Meeting and Exhibit, Reno, NV, 10-13 January 2005, Paper AIAA-2005-0253.

Reinking, R.F., R.A. Kropfli, S.Y. Matrosov, W.C. Campbell, M.J. Post, D.A. Hazen, J.S. Gibson, K.P. Moran and B.E. Martner, 2001: Concept and Design for a Pilot Demonstration Ground-Based Remote Icing Detection System. *30th International Conference on Radar Meteorology*, Munich, Germany, July 2001, P5.2.

Schneider, T.L., B.C. Bernstein and R.A. Reinking, 2005: Forecasting and ground-based remote icing detection system (GRIDS): Documentation of the transition from a glaciated environment to an SLD icing environment. AIAA 43rd Aerospace Sciences Meeting and Exhibit, Reno, NV, 10-13 January 2005, Paper AIAA-2005-0257.

Sheppard, B.E., 1990: The measurement of raindrop size distributions using a small Doppler radar. *J. Atmos. Oceanic Technol.* 7, 255-268.

Sheppard, B.E., R.E. Stewart, G.A. Isaac and T.B. Low, 1991: Nonlinear optimal estimation of temperature and integrated water vapour and liquid using a ground-based microwave radiometer in coastal winter storms. J. *Atmos. Oceanic Tech.*, 8, 812-825.

Sheppard, B.E., and P.I. Joe, 1994: Comparison of Raindrop Size Distribution Measurements by a Joss-Waldvogel Disdrometer, a PMS 2DG Spectrometer and a POSS Doppler Radar. *J. Atmos. Oceanic Technol.* 11, 874-887.

Sheppard, B.E., and P.I. Joe, 2000: Automated Precipitation Detection and Typing in Winter: A Two Year Study. *J. Atmos. Oceanic Technol.* 17, 1493-1507.

Wolde., M., Marcotte, D., Jordan, J.,Isaac, G. A., Cober, S. G., and Haimov, S., 2005: Airborne radar observations of icing in winter clouds during AIRS II. AIAA 43rd Aerospace Sci. Meeting and Exhibit, Reno Nevada, 10-13 January 2005, Paper AIAA-2005-0254.

Zawadzki, I., W. Szyrmer, and S. Laroche, 2000: Diagnostic of supercooled clouds from single-Doppler observations in regions of radar-detectable snow. J. Applied Meteor., 39, 1041-1058.