P8.5 TROPOSPHERIC AIRBORNE METEOROLOGICAL DATA REPORTING (TAMDAR) ICING SENSOR PERFORMANCE DURING THE 2003 ALLIANCE ICING RESEARCH STUDY (AIRS II)

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1. INTRODUCTION

The Tropospheric Airborne Meteorological Data Reporting (TAMDAR) sensor was deployed onboard the University of North Dakota Citation II aircraft in the Alliance Icing Research Study (AIRS II) from Nov 19 through December 14, 2003. TAMDAR is designed to measure and report winds, temperature, humidity, turbulence and icing from regional commercial aircraft (Daniels et. al., 2004).

TAMDAR icing sensor performance is compared to a) in situ validation data from the Citation II sensor suite, b) Current Icing Potential products developed by the National Center for Atmospheric Research (NCAR) and available operationally on the NOAA Aviation Weather Center's Aviation Digital Data Server (ADDS) and c) NASA Advanced Satellite Aviation-weather Products (ASAP) cloud microphysical products.

2. ALLIANCE ICING RESEARCH STUDY II

The second Alliance Icing Research Study occurred in the vicinity of Mirabel, Quebec during the winter of 2003 to 2004. It was conducted by the bi-national Aircraft Icing Research Alliance, a cooperative effort between the National Research Council of Canada, NASA, NOAA, the FAA and major government and university research laboratories in the U.S. and Canada. AIRS II was the second major field study conducted to: a) develop techniques to remotely detect, diagnose and forecast hazardous winter conditions at airports, b) improve weather forecasts of aircraft icing conditions, c) improve characterization of the aircraft icing environment and d) improve our understanding of the icing process and its effect on aircraft (Hallet, et al., 2003). AIRS II data was collected to: a) investigate the conditions associated with super-cooled large drop formation, b) determine conditions governing cloud glaciation, c) document the spatial distribution of ice crystals and super-cooled 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.

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3. TAMDAR ICING CASE STUDIES

AIRS II provided the NASA Aviation Safety Program's Aviation Weather INformation (AWIN) element an opportunity to test the performance of the TAMDAR instrument in various in-flight icing scenarios. Four icing missions were examined. These occurred on November 24, 28, 30 and December 11, 2003. In all cases, TAMDAR Icing reports were compared to instrumentation onboard the UND Citation and to the Current Icing Potential product. NASA Langley Cloud microphysical products were useful for the icing study area only on November 30 due to a heavy cirrus overcast during the period of interest on the other three days. The November 30 case is presented in detail since comparison data were available for all validation systems on that day. Data from the other three days can be found in the appendix, Section 7.

3.1 Nov 30, 2003 Icing Mission

The Citation left Bangor, Maine at 1624Z, arriving at 35,000 ft. over the Mirabel airport outside of Montreal, Canada at 1730Z. A spiral descent was made over the runway intersection down to 4,000 ft. Clouds were not encountered until about 7200 ft, where there was a layer approximately 1000 ft thick. Lower clouds tops were observed just above 4,000 ft. Several passes were made along the runway at 4,000 ft in and out of cloud along the way. In cloud, the Citation encountered light to moderate rime ice and liquid water contents of 0.1 to 0.4 g/m3. This was followed by a missed approach over the runway from 4,000 ft. The cloud extended down to slightly below 2,000 ft. This was followed by passes at 7,000 ft. This profile was carried out several times. In general, the liquid water content was higher in the upper cloud layer, with larger mean values of the droplet sizes. There were a few ice crystals in both layers, but the clouds were composed primarily of water droplets. The clouds were well characterized by the measurements in the horizontal as well as the vertical. The Citation flight track is shown in Fig. 1 overlaying the 1815Z GOES-12 visible image. Time segments are shown as different colors. The inset shows the vertical variation of the aircraft during the flight.

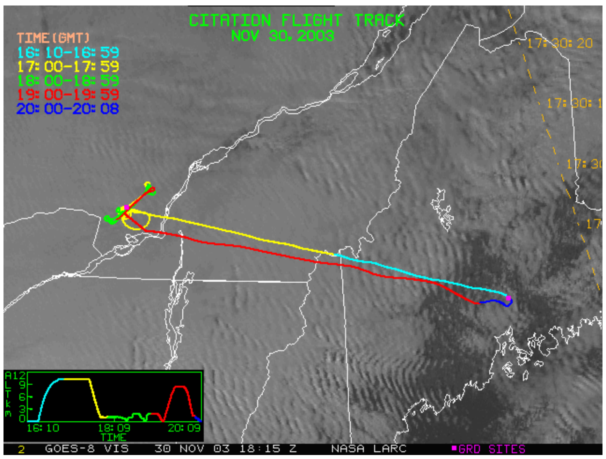

Figure 1 Nov 30, 2003 Citation II track on GOES VIS.

3.2 TAMDAR ICING SENSOR

Figure 2 is a close-up view of an un-mounted TAMDAR probe. The dimensions of the aerodynamic section (shown with a bright silver finish) of the probe are approximately 4 centimeters by 10 centimeters. The signal processing unit (black box) resides within the fuselage or wing and measures approximately 10 centimeters by 12 centimeters by 12 centimeters. The TAMDAR sensor was mounted to the UND Citation fuselage just behind and below the ship's pitot probe.

Figure 2 TAMDAR probe (side view).

TAMDAR is equipped with two independent infrared emitter/detector pairs mounted in a leading edge recess to detect ice accretion. Each pair is mounted such that their beams will be blocked if at least 0.5 millimeters of ice collects on the leading edge surface. Two emitter/detector pairs are utilized for redundancy and in case one pair become blocked by foreign material. The emitter/detector wavelengths were selected to detect all forms of ice accretion, namely rime, glaze, and mixed. Mounted within the aerodynamic section of the probe are internal heaters that melt the ice and the measurement cycle repeats. The heaters remain powered for at least one minute. The large electrical current flow to the probe affects the other measurements, so all data is flagged during deicing. The de-icing cycle repeats if more ice is detected. The TAMDAR sensor automatically processes all measurements into a single observation. A satellite modem using the Iridium short-burst text message data link is used to downlink each observation. Special observations are triggered by an icing onset. The minimum time between icing observations is 1 minute.

3.3 UND Citation Icing Instrumentation

The University of North Dakota owns and operates a Cessna Citation II aircraft (N77ND) for the purpose of atmospheric research. This aircraft type has a number of design and performance characteristics that make it an ideal platform for a wide range of atmospheric studies. The Citation II is a twin-engine fanjet with an operating ceiling of 43,000 feet (13.1 km). The turbofan engines provide sufficient power to cruise at speed of up to 340 knots (175 m/s) or climb at 3300 feet per minute (16.8 m/s). These high performance capabilities are accompanied by a relatively low fuel consumption at all altitudes, giving an on-station time of up to 4 hours or more, depending on mission type. Long wings allow it to be operated out of relatively short airstrips and to be flown at the slower speeds necessary for many types of measurements.

Figure 3 University of North Dakota Citation II.

The Citation is certified for flight into icing conditions. Cloud microphysical measurements are made with an array of Particle Measuring Systems probes (FSSP, 1D-C, 2D-C) mounted on the wing-tip pylons. These probes measure both liquid water content and icing rate.

UND Citation II Icing instrumentation showed significant correspondence with TAMDAR on November 30. Figure 4 compares the TAMDAR Icing Detector with the UND Citation Total Icing Detector and Water Content Detector. The TAMDAR detections are denoted by the upper row of "X" symbols on the plot. The lower row of Xs represents TAMDAR heater warnings and, while not icing detections, should not occur except when the heaters have been activated due to icing. They are shown as a secondary indication of icing as some data packets were lost due to communications link problems. The solid blue line labeled "ICE_DETv"" represents UND Citation parameter "Analog Channel 17 ICE Detector [volts]" normalized to a range of zero to one for display. Changes in the voltage are indicative of icing. The solid green line labeled "ICE_D_LWC" is UND Citation parameter "Ice Detector Liquid Water [gm/m^3]", and correlates well with periods of icing detection.

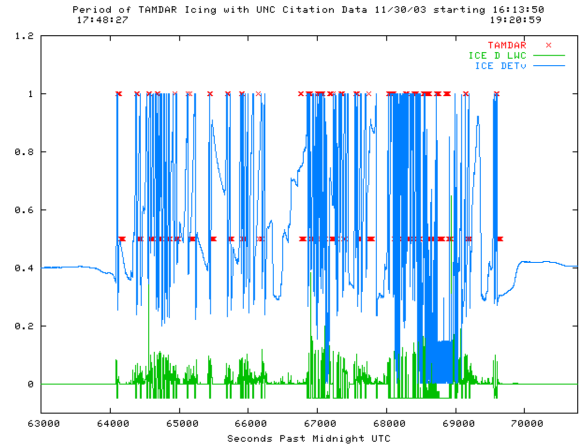

Figure 4 Nov 30 TAMDAR and Citation icing detection.

Although Figure 4 shows only a limited time segment during which the TAMDAR sensor detected icing, comparisons of longer data records show good correlation of icing detection and non-detection by TAMDAR with UND Citation icing indications. This qualitative comparison appears to indicate good performance in correct detections and correct null-detections, as well as good false alarm and missed detection performance. Further studies are planned to provide a more quantitative analysis of these results.

3.4 NCAR Current Icing Potential Product

The Current Icing Potential (CIP; Bernstein et. al 2004) produces an hourly diagnosis of the potential for icing and super-cooled large drops (SLD) over the CONUS and southern Canada. CIP combines observations from satellite, radar, METARs, and pilot reports of icing (PIREPs) with RUC model output to calculate these potential on a scale from 0 (no icing) to 1 (icing very likely). Figure 5 shows the icing potential at 18Z on November 30 at 4000 ft. Dark red denotes areas of high icing potential.

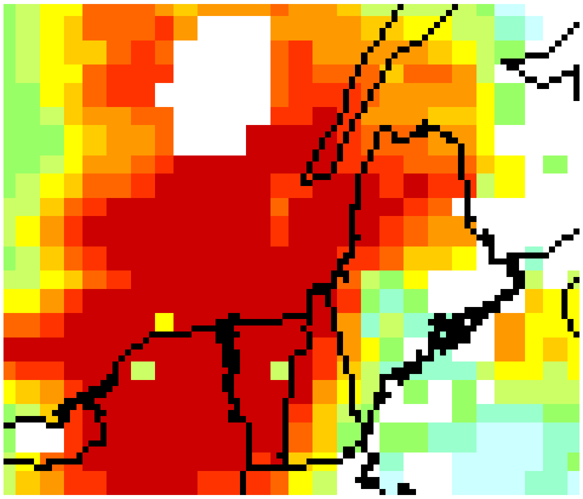

Figure 5 November 30 CIP for FL 040.

3.5 NASA Satellite Icing Products

Figure 6 compares the performance of the TAMDAR sensor to the in-flight icing probability estimated from 4-km cloud microphysical products derived from GOES data at NASA Langley Research Center. This analysis is detailed in Nguyen et al. 2004. The satellite products are graphical depictions of icing risk, cloud phase, droplet radius and effective cloud height (see Minnis et al. 2004). Examples of these products for the November 30 icing mission are depicted in Figs. 7 - 10. In figure 6, TAMDAR shows off-and-in icing throughout much of the cloud boundaries as estimated from GOES. The GOES cloud-top is higher than the 7,000 ft determined from the Citation, but the cloud base heights are nearly identical from the two data sets. During the last ascent, the TAMDAR indicates icing near 3 km (~10 Kft), which is quite close to the GOES cloud-top altitude. The TAMDAR, CIP and GOES results indicate significant icing potential in the same locations.

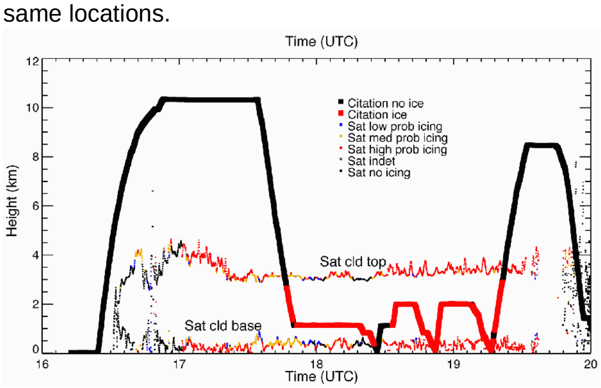

Figure 6 November 30 TAMDAR vs. GOES Icing Risk.

As indicated by the large red area in Fig. 7, the November 30 GOES satellite icing risk product indicated a predominately high risk of icing for the duration of the Citation's flight even though it was too high to sample the large area of icing except near Montreal. The results in Fig. 6 help confirm the extent of the icing risks identified from GOES data.

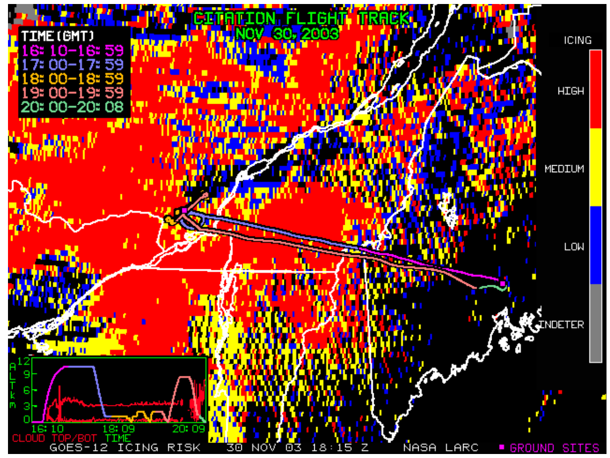

Figure 7 November 30 GOES satellite icing risk.

The corresponding cloud phase product (Fig. 8) shows a strong indication that the entire area is predominated by super-cooled liquid water (SLW; light blue corresponds to liquid water cloud with temperature T < 273 K), a factor that helps determine the icing risk. Not all of the SLW clouds are classified as having potential for icing (e.g., eastern Maine) because they are considered to be too thin. One goal of the icing flights is too help validate and refine the satellite icing products.

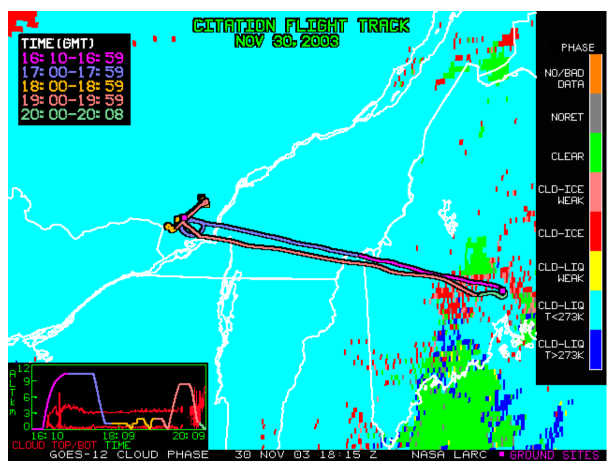

Figure 8 November 30 GOES Cloud Phase.

Satellite-derived effective droplet radius (Fig. 9) is another factor affecting the satellite determination of icing risk. The effective radii near Mirabel were quite large (13 - 19 μm radius) indicating a high probability for large (> 26 - 38 μm diameter) SLD near Mirabel. The smaller droplets north of Mirabel yield the no-icing potential areas seen in Fig. 7.

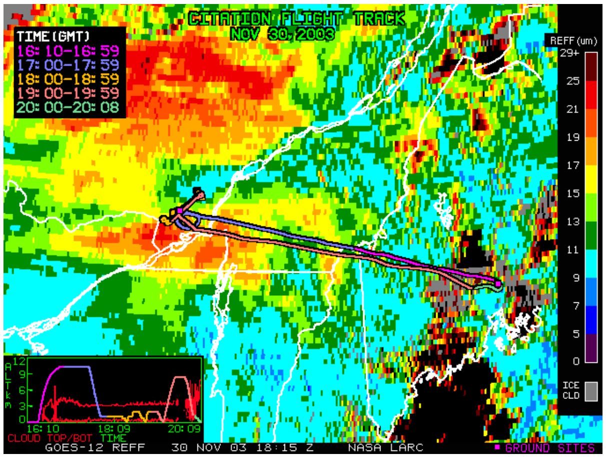

Figure 9 November 30 GOES Droplet Radius.

Effective cloud heights depicted in Fig. 10 correspond well with reports of icing conditions encountered at Mirabel on November 30 during repeated cloud transects at 4000 feet AGL. Airborne observations placed cloud tops near 7000 ft (2.1 km) and bases near 2000 ft (0.6 km) while the tops in Fig. 10 vary from 2 - 3.5 km in the Mirabel area.

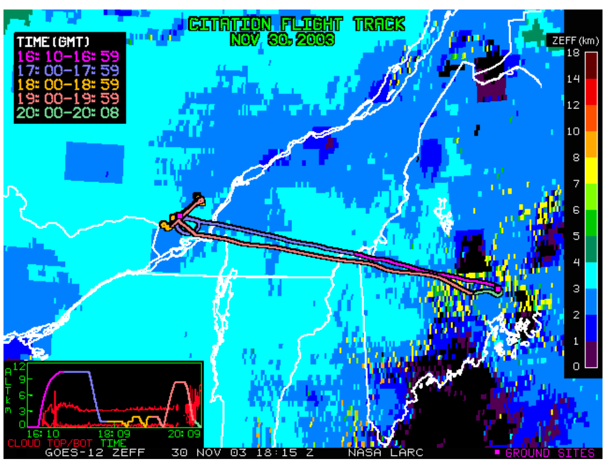

Figure 10 November 30 GOES Effective Cloud Height.

4. DISCUSSION AND CONCLUSIONS

The analysis and comparison of data collected onboard the UND Citation II over Mirabel, Quebec during the AIRS II flight campaign in November and December 2003 indicates that the TAMDAR sensor will detect light to moderate in-flight icing at flight levels typically flown by regional commercial aircraft and general aviation since severe icing conditions were not encountered. Further analyses of these data are needed to quantify TAMDAR performance as compared with the UND Citation II Rosemont instruments and other validations systems that were available during AIRS II.

5. ACKNOWLEDGMENTS

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7. APPENDIX

November 24 and 28 and December 11 cases are described in this appendix.

7.1 Nov 24, 2003 Icing Mission

The UND Citation departed Bangor to intercept a cold front approaching Mirabel. The front was expected to produce significant icing during that evening and the early morning hours of the following day. The Citation was to position in Ottawa with the expectation of flying an early morning mission during the icing event on Tuesday, November 25. The Citation flew past Ottawa to penetrate the frontal zone and to measure the cloud microphysics before the system reached Ottawa. The aircraft took off from Bangor, ME at 1808 UTC and flew through the frontal zone to London, Ontario. Cloud microphysics data were collected at several temperature levels in the frontal system. The Citation then turned back to the east to pass through the frontal zone again and landed in Ottawa at 2155 UTC. The total flight time for the mission was 3.8 hours. Figure A-1 is germane.

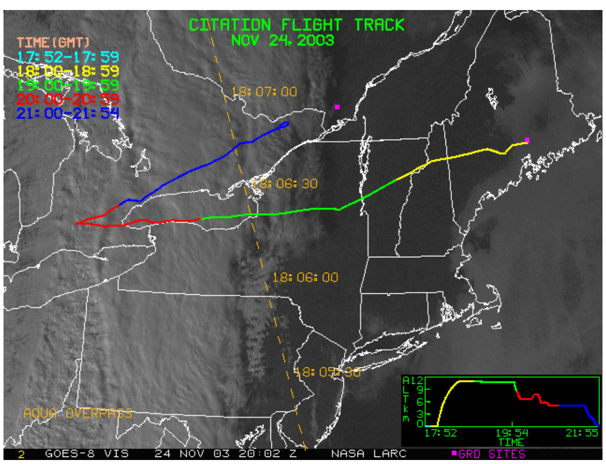

Figure A-1 Nov 24, 2003 Citation II track on GOES VIS.

A comparison of TAMDAR icing detection on November 24 with the UND Citation's instrumentation is shown in figure A-2. Good correspondence between TAMDAR and Citation instrumentation for the detection of icing and null conditions is also indicated for this case.

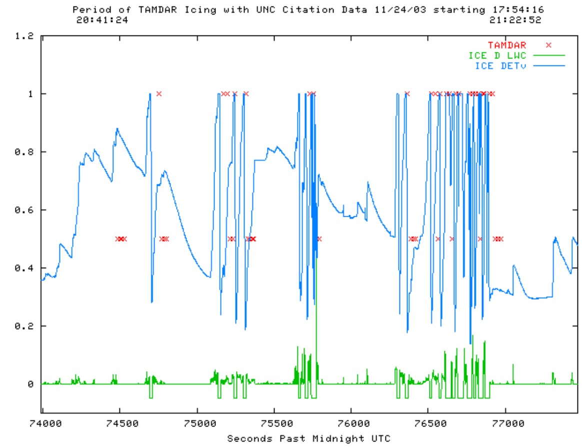

Figure A-2 Nov 24 TAMDAR/UND Citation Comparison.

The NCAR/NWS Current Icing Potential product for flight level FL160 on November 24 indicated the potential for icing along the western part of the flight route at 21Z (Fig. A-3). It also shows that the region over Lake Ontario contained a moderate icing environment at flight level.

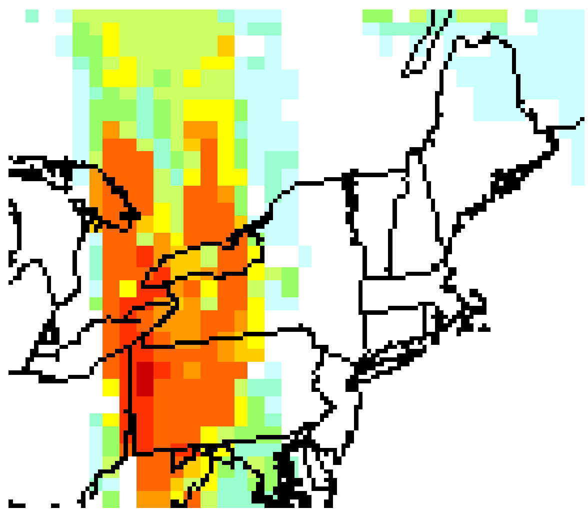

Figure A-3. As in Fig. 5 for FL160 at 21Z, November 24.

7.2 Nov 28, 2003 Icing Mission

The Citation took off at 1657Z and arrived at the runway intersection of Mirabel at 1813Z and did a spiral descent from 35,000 to 2000 ft. Cloud tops at this time were at 27,000 ft. After the descent, the aircraft climbed to 8,000 ft and made passes along the 06/24 runway in 2000 ft increments up to 18,000 ft. The Citation then did a spiral ascent up to cloud tops, which were at about 29,000 ft. with a few convective elements reaching 29,500 ft. During the passes along the runway, the

Citation encountered mostly ice crystals with a few patches of SLW at various times and elevations. Cloud tops at the west end of the legs were much lower than at the east end. The aircraft was out of cloud at 18,000 ft at the west end. The spiral ascent at the east end had tops over 29,000 ft. The aircraft finished the ascent at 2002Z, fueled at Montreal and returned to Bangor. The trip from Montreal to Bangor showed clouds consisting almost entirely of ice crystals at altitudes above the melting level. The Citation landed at 0011Z, Nov 29.

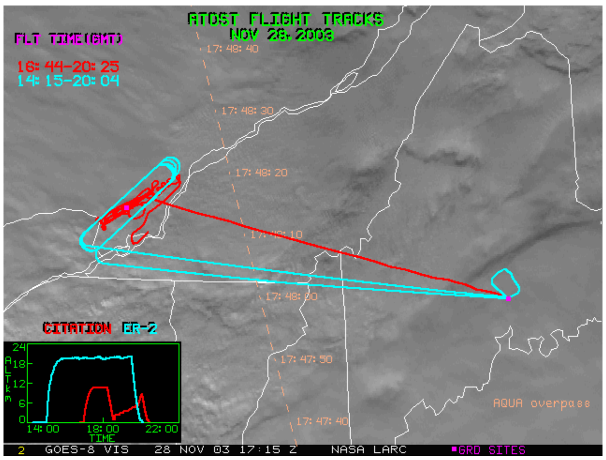

Figure A-4 Nov 28, 2003 Citation II track on GOES VIS.

A comparison of TAMDAR icing detection on November 28 with the UND Citation's instrumentation is shown in figures A-5 and A-6.

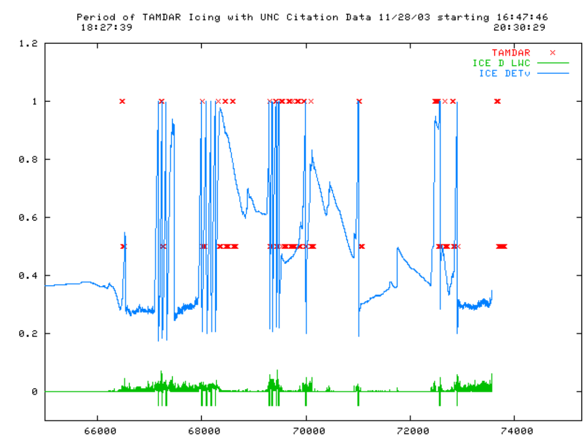

Figure A-5 Nov 28 TAMDAR/UND Citation Comparison.

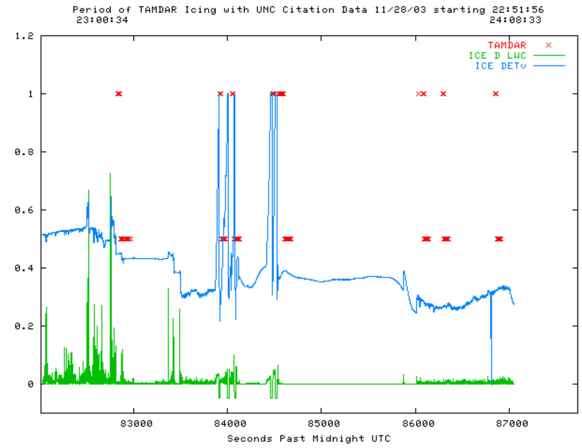

Figure A-6 Nov 28 TAMDAR/UND Citation Comparison.

The NCAR/NWS Current Icing Potential product on November 28 (Fig. A-7) indicated the potential for icing over YMX at the altitudes sampled.

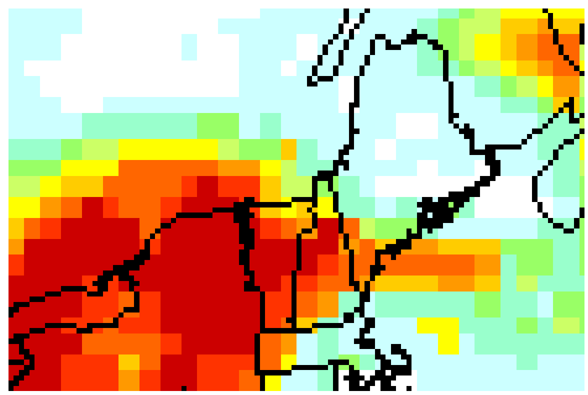

Figure A-7. As in Fig. A3 for FL 120 at 19Z November 28.

7.3 Dec 11, 2003 Icing Mission

The Citation took off from Bangor at 1519Z, and arrived over Mirabel at 35,000 ft at 1614Z. A spiral descent over the "garage" site encountered cloud tops at 29,500 ft. The clouds at the high elevations were composed of ice crystals. There were several layers of cloud during the descent, but no liquid water was encountered until 11,000 ft, where there were small patches of relatively low (less than 0.2 g/m3). The sounding went down to 3,000 ft (T=+2.6C), where there were precipitation sized water drops. The super-cooled water was between about 11,000 and 8,000 ft. Horizontal transects were made in 1,000 ft intervals parallel to runway 06/24 between these altitudes and a missed approach from 11,000 ft down to 250 ft. The citation then climbed to 29,000 ft to within an estimated

500 ft of cloud top at 1838Z. The aircraft then landed in Montreal at 1858Z.

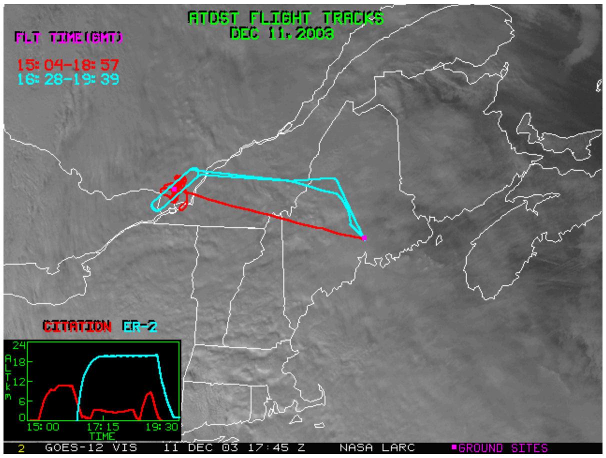

Figure A-8 Dec 11, 2003 Citation II track on GOES VIS.

A comparison of TAMDAR icing detection on December 11 with the UND Citation's instrumentation is shown in figure A-9. Correlation is evident for stronger signals but analysis of thresholds for weak and null cases continues.

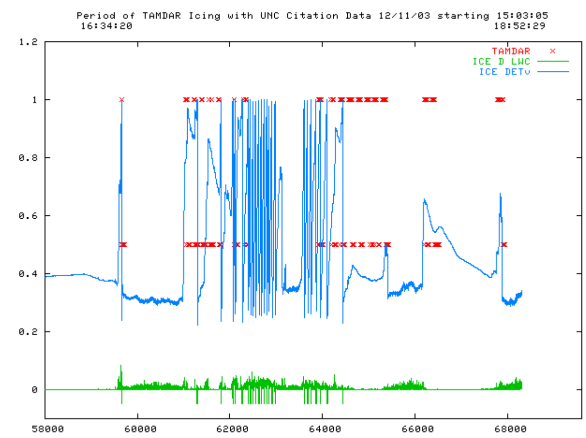

Figure A-9 Dec 11 TAMDAR/UND Citation Comparison

The NCAR/NWS Current Icing Potential product for flight level FL100 on December 11 indicated a high potential for icing along most of the flight track (Fig. A-10).

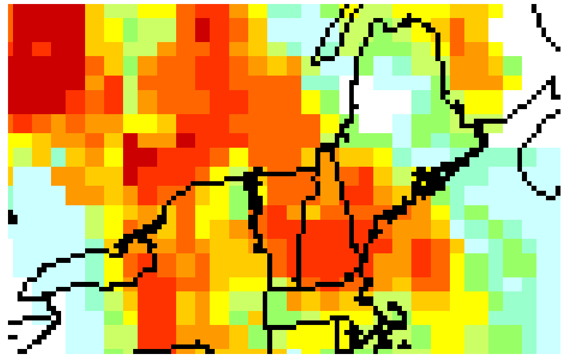

Figure A-10 As in Fig. A7 for FL 100 at 19Z November 28.