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Recent Canadian Research on Aircraft In-Flight Icing

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ABSTRACT

A cooperative research program on aircraft in-flight icing, between the National Research Council of Canada and the Meteorological Service of Canada, has been active since the 1950s. Most recently, the Canadian Freezing Drizzle Experiment (CFDE) and the Alliance Icing Research Study (AIRS) were organized to characterize icing environments associated with freezing drizzle; develop better techniques for forecasting such events; and develop our ability to remotely detect icing regions. These field projects, involving instrumented aircraft, were conducted out of Newfoundland (March, 1995) and Ontario (1996/97, 1997/98, and 1999/00). Newfoundland and the Great Lakes are the two regions in North America with the highest frequency of freezing precipitation at the surface. Freezing drizzle, or supercooled large drops (SLD), is considered to be a dangerous icing condition that is not covered by current aircraft certification procedures. The median liquid water contents measured in clouds in both regions were similar, while the droplet concentrations and the frequency of occurrence of mixed phase clouds tended to be higher in Ontario. In both Newfoundland and Ontario, conditions with SLD were often found outside the envelopes used to certify aircraft for in-flight icing. Approximately 80% of the SLD environments were assessed to have formed through a non-classical formation mechanism. Forecasting icing conditions remains a challenge. Although new, more physically realistic, in-flight icing forecast schemes have been developed, verification of these forecasts, using the *in situ* aircraft data, shows that considerable improvement can still be made.

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INTRODUCTION

The primary objectives of the recent Canadian aircraft in-flight icing research have been to:

a) characterize the icing environment associated with freezing precipitation or supercooled large drops (SLD);

b) develop better techniques for forecasting such events; and

c) improve the capability for identifying regions of potentially hazardous aircraft icing with remote sensing instruments, such as microwave radiometers, satellites, and radars.

Measurement campaigns have been conducted out of St. John’s, Newfoundland (1995), and Ottawa, Ontario (1996/97, 1997/98 and 1999/2000). These projects grew out of previous aircraft icing research by this group, which was reported by Isaac (1991) and Cober *et al*. (1995, 1996), and the much earlier work described by Pettit (1954).

The rationale for the renewed interest in aircraft icing largely comes from the October 1994 crash near Roselawn, Indiana, of an ATR-72 commuter aircraft. The primary cause of the accident has been attributed to icing associated with freezing drizzle (Marwitz *et al*., 1996). A ridge of icing built up behind the de-icing boots, which led to a roll instability in the aircraft and, ultimately, to the aircraft crash. The accident focused attention on the fact that the certification test environments used by Transport Canada, the Joint Aviation Authority and the Federal Aviation Administration for certifying aircraft for flight into icing conditions, do not include icing environments associated with freezing precipitation. These certification environments only extend to cloud droplet median volume diameters of 40-50 microns; while, in reality, median volume diameters as large as 1,000 microns have been measured. This implies that aircraft have been certified for flight into icing conditions, without actually having been demonstrated to operate safely under the potentially hazardous icing conditions associated with freezing precipitation. While the regulatory agencies are not requiring aircraft to re-certify, they have indicated that *in situ* data are urgently needed to characterize these icing environments. This problem was re-enforced when an Embraer-120 twin-engine turbo-prop aircraft crashed on approach into Detroit on 9 January 1997. Once again, airframe icing appeared to be the primary cause of the accident.

Few significant sources of data describing icing associated with freezing precipitation existed prior to the beginning of this fieldwork in 1995. More recently, Politovich (1989) discussed several case studies of aircraft icing caused by large

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RÉSUMÉ

supercooled droplets. Some early results from the Canadian Atlantic Storms Experiment were described by Cober *et al*. (1995), and a particularly hazardous case was documented by Cober *et al*. (1996). Ashenden and Marwitz (1997) summarize some of the early measurements made in the U.S.

In situ measurements are extremely important. Regulatory agencies, aircraft designers, flight test engineers and pilots must know the liquid water content and drop sizes that occur during icing associated with SLD or freezing drizzle, as well as having statistics on the horizontal and vertical extents of the phenomena. This knowledge will allow a better assessment of the hazards associated with these conditions, which are largely unknown at present. Other than pilot judgement, there are no general prohibitions from flying in such conditions. The development of an extensive database may lead to new regulations, possible new certification rules and better action plans for pilots when they encounter such conditions.

The first Canadian Freezing Drizzle Experiment (CFDE I) was conducted out of St. John's, Newfoundland, during March 1995, using the National Research Council (NRC) Convair-580 (**Figure 1**). Freezing precipitation was encountered on 11 of the 12 CFDE I project flights. CFDE II was conducted out of Ottawa, using the NRC Twin Otter, during December 1996 to January 1997, with a total of four project flights. This was mainly a test project to determine whether it was logistically feasible to conduct a project in the high traffic area of the Great Lakes. CFDE III was conducted out of Ottawa from December 1997 to February 1998, using the NRC Convair-580. There were 26 project flights flown during this project, and freezing drizzle was encountered on 19 of these flights. The Alliance Icing Research Study (AIRS), which included many U.S. participants, was conducted between November 1999 and February 2000, operating out of Ottawa, but with a remote sensing site located near Mirabel airport in Quebec. There were 25 Convair-580 flights, plus 16 flights with a NASA Twin Otter and four flights with a Learjet leased by Stratton Park Engineering Corporation of Boulder, Colorado. This paper will summarize some of the findings of this fieldwork, emphasizing the Convair-580 measurements, as well as some complementary studies.

CLIMATOLOGY

During Canadian winters, many weather hazards to aviation exist. Stuart and Isaac (1994) characterized the frequency of occurrence, and precipitation amounts, of the precipitation types associated with many aviation hazards, including dry snow, wet snow, ice/snow pellets, freezing rain and freezing drizzle. This analysis indicated that hazards are more severe on the Canadian east coast, in comparison to central and western Canada. If freezing precipitation at the ground is considered as an indicator of the frequency of occurrence of SLD aloft, then the climatology of freezing precipitation, prepared by Stuart and Isaac (1999), showed that the maximum frequency of freezing precipitation (drizzle and rain), of 150 hours per year, occurs near St. John's, Newfoundland. There is also a secondary maximum in the Great Lakes region, of approximately 50 to 75 hours per year. Considering the greater

Figure 1.
The National Research Council Convair-580 as used during CFDE and AIRS.

air traffic in the Great Lakes region, the total risk to aircraft is greater in this area. So, CFDE I was conducted in the region with the highest frequency of occurrence of freezing precipitation (St. John's); and CFDE II and III, and AIRS, were conducted near the secondary maximum (Ottawa).

Figure 2 shows the frequency of occurrence of freezing rain and drizzle as a function of surface temperature and maximum upper air temperature for St. John's. Approximately 15% of the freezing rain events, and 60% of the freezing drizzle events, have no warm layer aloft with temperatures warmer than 0ºC. An analysis of the individual temperature profiles also shows that many of the freezing precipitation events that occurred, with a warm layer aloft, formed in cloud that was entirely at temperatures colder than 0ºC (Strapp *et al*., 1996).

The classical mechanism for formation of freezing precipitation involves ice crystals or snow flakes falling into a warm layer, melting, and then supercooling in a colder sub-freezing layer near the surface. Stewart (1992) described this mechanism in detail. However, it appears that a considerable fraction of freezing precipitation, greater than 50% for freezing drizzle at St. John's, forms entirely at temperatures colder than 0ºC. Even near Maniwaki and Inuvik (**Table 1**, from Strapp *et al*., 1996), the frequency of occurrence of this non-classically formed freezing precipitation is significant. Although this conclusion has been reached in other studies (*e.g*., Huffman and Norman, 1988), it is only recently receiving full recognition. The exact mechanism through which such large drops form is poorly understood, and this makes it difficult to effectively forecast such events.

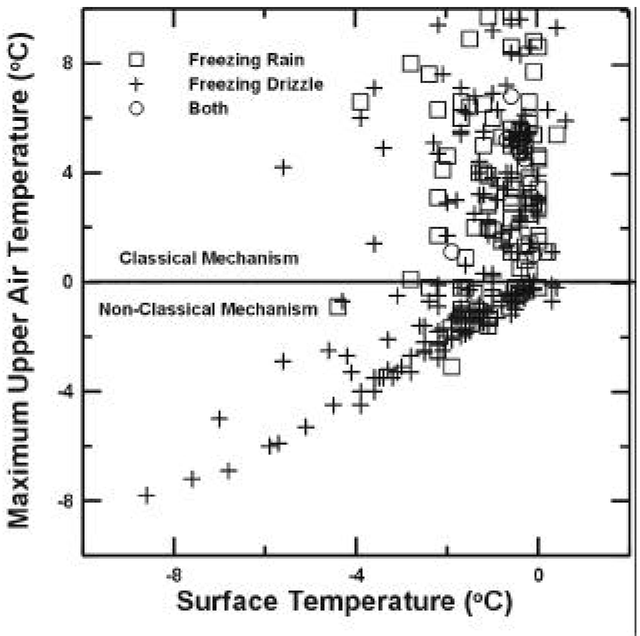

Figure 2.
Freezing precipitation (1971-1992) at St. John's, Newfoundland, as a function of surface temperature and the maximum temperature aloft.

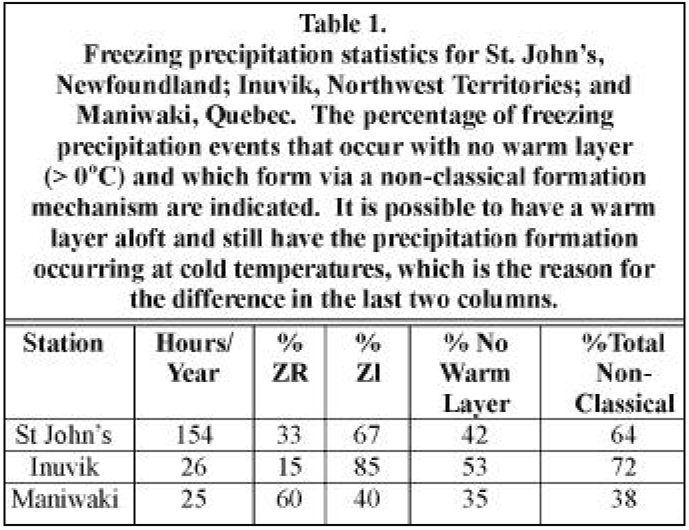

Table 1.
Freezing precipitation statistics for St. John's, Newfoundland; Inuvik, Northwest Territories; and Maniwaki, Quebec. The percentage of freezing precipitation events that occur with no warm layer (> 0°C) and which form via a non-classical formation mechanism are indicated. It is possible to have a warm layer aloft and still have the precipitation formation occurring at cold temperatures, which is the reason for the difference in the last two columns.

Station	Hours/ Year	% ZR	% ZL	% No Warm Layer	%Total Non-Classical
St John's	154	33	67	42	64
Inuvik	26	15	85	53	72
Maniwaki	25	60	40	35	38

INSTRUMENTATION

The NRC Convair-580 aircraft was instrumented with Particle Measurement System (PMS) probes (FSSP, 2DC-Mono, 2DC-Grey, 2DP-Mono, PCASP, etc.) to measure particle concentrations and sizes. Cloud liquid water content (LWC) was measured with King (long and/or short) hot wire devices. A Nevzorov hot wire device for measuring LWC and total water content (TWC = liquid water content + ice water content) was also used for all four projects (Korolev *et al.*, 1998). For CFDE I, a Stratton Park Engineering Corporation (SPEC) holographic camera was used (Lawson *et al.*, 1998). A SPEC Cloud Particle Imager was installed on the belly of the aircraft for CFDE III, and on the port wing for AIRS. A Desert Research Institute (DRI) Cloudscope and Replicator were installed at wing tip locations. A Rosemount icing detector (Cober *et al.*, 2001c) was installed for all three projects, and a Vibrometer ice detector was added for CFDE III and AIRS. Icing rates were measured by videotaping an icing rod, which could be heated to remove the ice. A Rosemount 858 gust probe was used for CFDE I and III, and AIRS. For CFDE III and AIRS, a stereographic system was developed that measured the ice accretion on an antenna radome located on the top of the fuselage, just forward of the vertical fin.

IN SITU MEASUREMENTS

It is difficult to analyze the cloud microphysical data as obtained onboard the Convair-580. The analysis in this paper, which follows that of Cober *et al*. (2001b), uses mainly the PMS FSSP cloud droplet measurement probes, the hot wire probes (King and Nevzorov), the PMS 2D probes, the Rosemount icing detector, and the temperature sensor. Many of these probes have been calibrated within the NASA and NRC Icing Research Tunnels in Cleveland and Ottawa (*e.g.*, Strapp *et al*., 2000), and some (*e.g.*, PMS probes) are routinely calibrated during the field projects. Following the analysis technique of Cober *et al*. (2001a), the frequency of occurrence of 30 second (3 km) periods when the aircraft was in-cloud, that could be characterized as all liquid, mixed phase (liquid and ice) and glaciated (all ice), are summarized in **Table 3**. The maritime field project (CFDE I), performed out of Newfoundland, and the continental field projects (CFDE III and AIRS), conducted out of Ottawa, have been treated separately. There were only four flights during CFDE II, using the NRC Twin Otter, and these data are not being reported in this paper. For **Table 3**, in-cloud was defined as occurring at temperatures colder than 0 ºC, with a total water content (TWC) greater than 0.005 g m^{-3}. Glaciated clouds occurred more frequently during CFDE I, while mixed phase clouds occurred more often during the flights out of Ottawa. For both the continental and maritime field projects, at least 34% of the in-cloud conditions contained only the liquid phase.

Table 4 summarizes the cloud microphysical data for the maritime (CFDE I) and continental (CFDE III and AIRS) cases. **Table 4** differs from **Table 3** because it only includes liquid and mixed phase cases where the ice particle concentration was lower than 1 l^{-1}. Only under such low ice particle concentrations

Table 2.
Cloud microphysical instrumentation onboard the NRC Convair-580 during CFDE III and AIRS.

Instrument	Variable
Rosemount Temperature Probe	Temperature
Reverse Flow Temperature	Temperature
Cambridge Dewpoint Hygrometer	Dewpoint
University of Warsaw Temperature	High frequency temp variations
Rosemount 858 Probe	3 D wind gusts
King Probe (short and long types)	liquid water content
Nevzorov Probe	liquid and total water content
PMS PCASP	Aerosol (0.13-3 µm)
PMS FSSP 100x	Droplets (2-30 or 3-47 µm)
PMS FSSP 100x	Droplets (5-95 µm)
PMS 2DC Mono	Particles (25-800 µm)
PMS 2DC Grey	Particles (25-1600 µm)
PMS 2DP Mono	Particles (200-6400 µm)
SPEC Cloud Particle Imager	Particles (>2.5 µm)
Desert Research Institute Replicator	Particles
Desert Research Institute Cloudscope	Particles
Rosemount Icing Detector	Icing Rate
Vibrometer Icing Detector	Icing Rate
Airbus Certification Rod	Icing Rate
LIDAR (1064 nm) up and down	
Ka-Band Cloud Radar*	

* AIRS Only

Table 3.
Percentage of time the Convair-580 was in-cloud at temperatures ≤ 0 °C and encountered liquid, mixed and glaciated conditions during the CFDE I, III and AIRS.

	CFDE I (maritime)	**CFDE III and AIRS (continental)**
In-Cloud: Ta ≤ 0 °C, TWC ≥ 0.005 g m^{-3}		
30 second or approximately 3km averages		
Number of In-Flight Points	6339	22604
% of Time In-Cloud, Ta ≤ 0 °C	37%	35%
% Liquid Phase	42%	34%
% Mixed Phase	25%	49%
% Glaciated	33%	17%

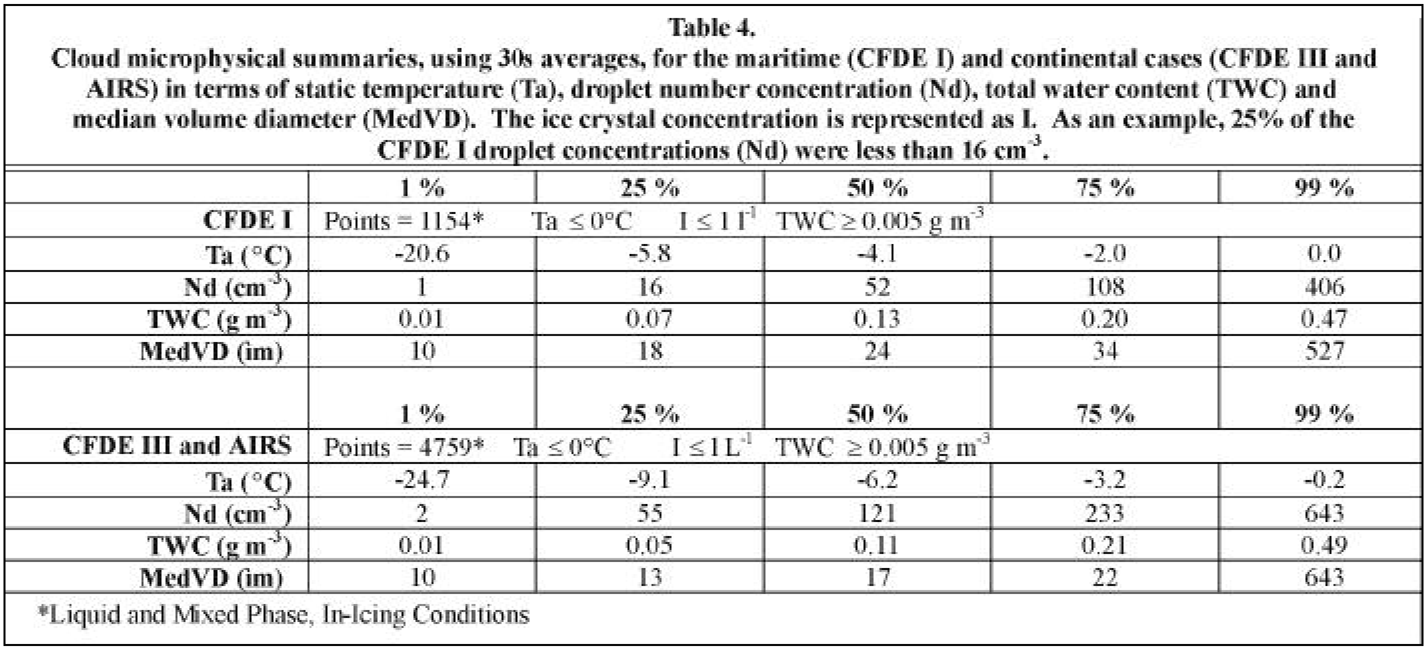

Table 4.
Cloud microphysical summaries, using 30s averages, for the maritime (CFDE I) and continental cases (CFDE III and AIRS) in terms of static temperature (Ta), droplet number concentration (Nd), total water content (TWC) and median volume diameter (MedVD). The ice crystal concentration is represented as I. As an example, 25% of the CFDE I droplet concentrations (Nd) were less than 16 cm^{-3}.

	1 %	25 %	50 %	75 %	99 %
CFDE I	Points = 1154* Ta ≤ 0°C I ≤ 1 l^{-1} TWC ≥ 0.005 g m^{-3}				
Ta (°C)	-20.6	-5.8	-4.1	-2.0	0.0
Nd (cm^{-3})	1	16	52	108	406
TWC (g m^{-3})	0.01	0.07	0.13	0.20	0.47
MedVD (im)	10	18	24	34	527
	1 %	**25 %**	**50 %**	**75 %**	**99 %**
CFDE III and AIRS	Points = 4759* Ta ≤ 0°C I ≤ 1 L^{-1} TWC ≥ 0.005 g m^{-3}				
Ta (°C)	-24.7	-9.1	-6.2	-3.2	-0.2
Nd (cm^{-3})	2	55	121	233	643
TWC (g m^{-3})	0.01	0.05	0.11	0.21	0.49
MedVD (im)	10	13	17	22	643

*Liquid and Mixed Phase, In-Icing Conditions

can one accurately measure the droplet concentration and size, and obtain particle size spectra (Cober *et al*., 2001a). The median temperature for the measurements was approximately -5 ºC, for both locations. The total water content (liquid plus ice) distribution was remarkably similar for both projects, well within the error of the instruments (10-15%). The droplet concentration was higher and the droplet median volume diameter was lower for the continental cases, which is consistent with known differences in clouds originating in maritime and continental environments.

ICING ENVIRONMENTS

Conventional icing by small (< 50 µm) supercooled droplets was studied in great detail during the 1950s and 1960s, and the measurements were used to generate the FAA Regulation 25 Appendix C (FAR 25-C) envelopes (Federal Aviation Administration, 1999). Aircraft approved to fly in icing conditions are certified against these envelopes. The FAR 25-C envelopes for 0, -10 and -20 ºC are plotted and labelled on **Figure 3**. These represent the continuous icing envelopes for 17.6 nm encounters (approximately 33 km). There exists another set of certification criteria for intermittent conditions, which mainly apply to convective clouds. Most of the clouds encountered during these field projects were stratiform in nature and, thus, the continuous envelopes are the most appropriate to use.

Also plotted on **Figure 3** are the 300 second (30 km) averaged data obtained during the CFDE I (top panel), and CFDE III and AIRS (bottom panel), averaged over all of the icing episodes encountered with temperatures between -40 ºC and 0 ºC, and all liquid or mixed phase conditions with ice particle concentrations less than 1 l^{-1}. The CFDE I data represents marine clouds for the most part, while the CFDE III and AIRS data represent continental clouds. It should be mentioned that the average liquid water content decreases by approximately 25% when the averaging scale increases from 30s (3 km) to 300s (30 km), indicating the variability of this parameter (Cober *et al*., 2001b). Since the FAR 25-C curves were designed for approximately 33 km distances, the 300s averaging interval for the new data presented here was used for comparison. Also indicated in **Figure 3** are 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. It is obvious, from **Figure 3**, that conditions that fell outside the FAR 25-C envelopes (the open symbols) were encountered relatively frequently and that, by the Newton criteria, the conditions were occasionally moderate to severe.

Table 5 summarizes the 30s (3 km) averaged icing data, and indicates that a large fraction of the in-flight icing encounters (73% for CFDE I, 41% for CFDE III and AIRS) contained some SLD (drops greater than 50 µm in diameter). Most (80%) of the observed SLD was formed through a non-classical formation mechanism, as described in the climatology section. As mentioned earlier, the exact mechanism for the formation of large drops through the non-classical mechanism is not known, although Pobanz *et al*. (1994) and Korolev and Isaac (2000), among others, have examined this problem. **Table 5** indicates the FAR 25-C conditions were exceeded for 20% and 6% of these 30s in-flight icing encounters during CFDE I and CFDE III/AIRS respectively. Under the Newton definitions, more than 50% of the encounters can be classified as light to moderate, with severe icing being encountered 0.2-0.3% of the time. The frequency of occurrence for the hazardous conditions of Politovitch (1989) and Ashenden and Marwitz (1997) are also given. The CFDE data and the exceedance criteria have been described in more detail by Cober *et al*. (2001b).

The mechanism of icing by SLD has been studied by Boutanios *et al*. (1998), who used a numerical model of the Convair-580 fuselage to show that small cloud droplets impinge onto the nose of the aircraft, while larger droplets, which do not necessarily follow the stream lines of flow around the aircraft, impact further and further back on the nose and the

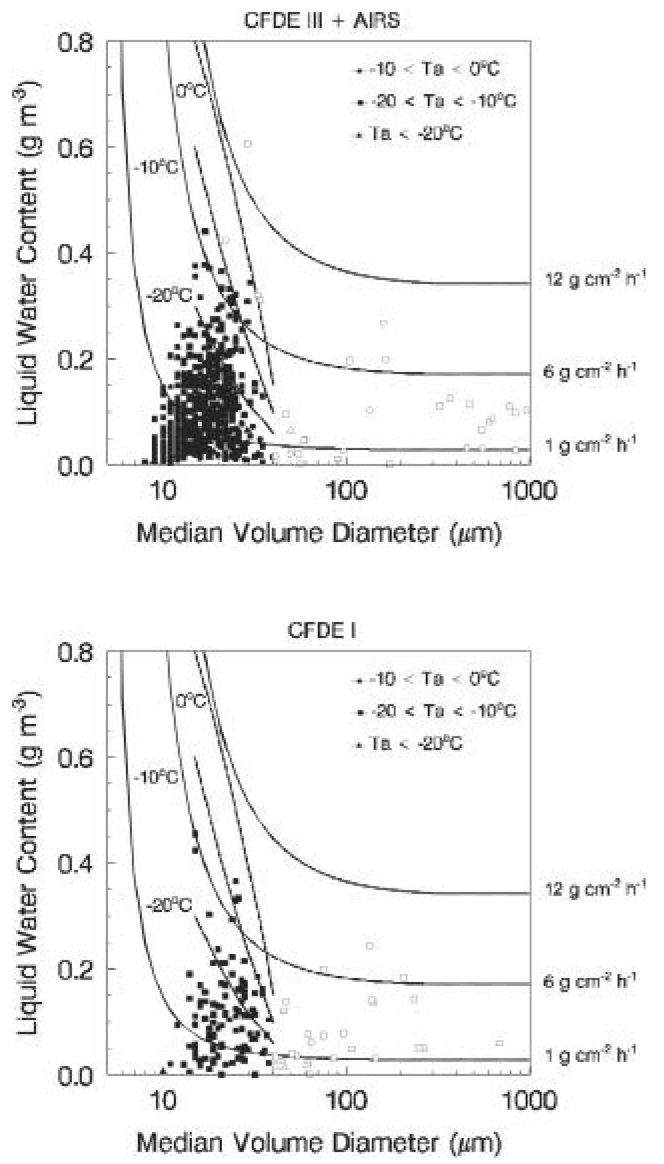

Figure 3.
CFDE I (top panel) and CFDE III and AIRS (bottom panel) 300 s (30 km) averaged data plotted against the FAR 25 Appendix C envelopes for 0, -10 and -20 °C, and the Newton envelopes for light (1 g cm^{-2} h^{-1}), moderate (6 g cm^{-2} h^{-1}) and severe (12 g cm^{-2} h^{-1}) icing. Open symbols represent points that are outside of the FAR 25C envelopes at the corresponding temperature.

aircraft fuselage. Thus, the pilot and co-pilot's side windows generally become more ice-contaminated as the size of the droplets increases. In fact, for some commuter aircraft, the pilots are advised to look at their side windows to determine if they are in SLD icing. This is the real danger of SLD, because droplets can impinge on larger surface areas, including surfaces aft of the normally protected leading edges.

Aircraft icing observed during CFDE and AIRS was usually light or moderate, with no obvious loss in performance of the aircraft. However, the aircraft did encounter areas that sufficiently worried the pilots that they exited the region to melt off the accreted ice. During CFDE III, there were three instances of runback icing where supercooled droplets overwhelmed the thermal (hot leading edge) anti-icing system, and water ran back over the wing surfaces and froze in chord-wise parallel rivulets. On some occasions during CFDE III, tail plane icing was observed. Icing on the tail is exceptionally dangerous because of the pilot's inability to see the ice forming, and the fact that the pilot's procedures for reacting to performance or control problems associated with tail icing are considerably different than for icing on the wing. During AIRS, the Convair-580 experienced three runback, two to three tail plane, and three to four moderate-severe icing events, as judged by the flight crew in post flight de-briefings. As during CFDE III, icing was encountered at temperatures colder than -20ºC, and at least one of these events was severe.

On 17 February 1998 during CFDE III, on a flight into mid- and higher-level cloud ahead of an approaching frontal system, extensive measurements were made in a mixed-phase region over Lake Ontario between 17,000-21,000 ft, with temperatures as low as -20 ºC and supercooled drops to 300 microns. Maximum LWC was 0.2 to 0.3 g m^{-3} and the droplet concentrations were in the 30 to 50 cm^{-3} range. Photographs show that the rate of accumulation was large enough for ice to form over the leading de-iced part of the tail. The pilots rated the icing as severe on the Convair, and a Boeing 747 flying in the same area also reported severe icing. On one occasion during this event, the tail buffeted, requiring the pilot to increase the airspeed and to exit the area.

The most severe icing episode for the Convair-580 during AIRS occurred on 16 February 2000, over Mirabel, at 18,000 ft at the very cold temperature of -29 ºC. 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 4**), and ice appeared on the leading edge of the horizontal stabilizer, completely covering over the heated surface. On descent to warmer temperatures, water was observed to be running underneath this ice surface, which tenaciously remained attached. This icing encounter was severe enough that, after five minutes of operating in these conditions, the pilots first increased power by 20-30% to maintain the flight conditions and, shortly afterward, decided to ascend above cloud (18,500 ft) to de-ice. In all probability, the very low temperatures that were encountered in this case rendered the thermal anti-icing system less effective than normal.

For both of the severe icing episodes discussed above, the measured liquid water contents and median volume diameters indicate the aircraft was encountering conditions close to, or exceeding, the FAR 25-C curves of **Figure 3** at the measured temperatures, which is consistent with the flight crew's real-time assessment of the icing conditions as severe.

FORECASTING AIRCRAFT ICING

A major goal of this work is to develop better forecasting techniques to identify in-flight icing and freezing precipitation conditions. Since empirical icing forecast schemes, based only on temperature and relative humidity (*e.g.*, Appleman, 1954), suffer from significant deficiencies (Tremblay *et al.*, 1996a),

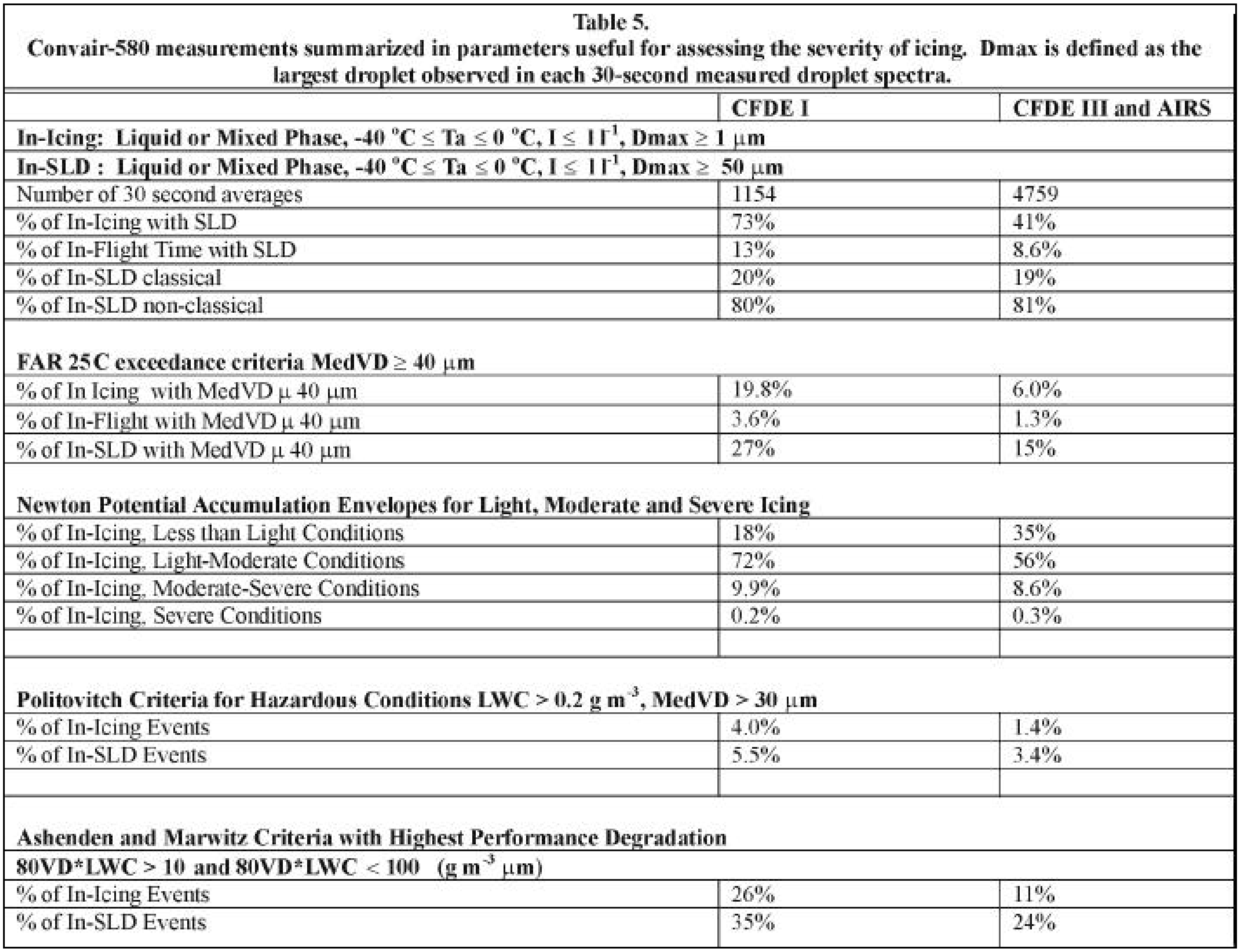

Table 5.
Convair-580 measurements summarized in parameters useful for assessing the severity of icing. Dmax is defined as the largest droplet observed in each 30-second measured droplet spectra.

	CFDE I	**CFDE III and AIRS**
In-Icing: Liquid or Mixed Phase, $-40\ ^{\circ}C \le Ta \le 0\ ^{\circ}C$, $I \le 1\ l^{-1}$, $Dmax \ge 1\ \mu m$		
In-SLD : Liquid or Mixed Phase, $-40\ ^{\circ}C \le Ta \le 0\ ^{\circ}C$, $I \le 1\ l^{-1}$, $Dmax \ge 50\ \mu m$		
Number of 30 second averages	1154	4759
% of In-Icing with SLD	73%	41%
% of In-Flight Time with SLD	13%	8.6%
% of In-SLD classical	20%	19%
% of In-SLD non-classical	80%	81%
FAR 25C exceedance criteria MedVD $\ge 40\ \mu m$		
% of In Icing with MedVD µ 40 µm	19.8%	6.0%
% of In-Flight with MedVD µ 40 µm	3.6%	1.3%
% of In-SLD with MedVD µ 40 µm	27%	15%
Newton Potential Accumulation Envelopes for Light, Moderate and Severe Icing		
% of In-Icing, Less than Light Conditions	18%	35%
% of In-Icing, Light-Moderate Conditions	72%	56%
% of In-Icing, Moderate-Severe Conditions	9.9%	8.6%
% of In-Icing, Severe Conditions	0.2%	0.3%
Politovitch Criteria for Hazardous Conditions LWC $> 0.2\ g\ m^{-3}$, MedVD $> 30\ \mu m$		
% of In-Icing Events	4.0%	1.4%
% of In-SLD Events	5.5%	3.4%
Ashenden and Marwitz Criteria with Highest Performance Degradation		
80VD*LWC > 10 and 80VD*LWC < 100 ($g\ m^{-3}\ \mu m$)		
% of In-Icing Events	26%	11%
% of In-SLD Events	35%	24%

data from CFDE I and an earlier project, the Second Canadian Atlantic Storms Program (CASP II), were used to develop a new, more physically realistic, aircraft icing scheme (Tremblay *et al*., 1995). This diagnostic icing forecast algorithm has already been implemented operationally, at the Canadian Meteorological Centre, to produce nation-wide aircraft icing forecasts. In order to test the improved skill of the new CMC scheme, Guan *et al*. (2001) used data from CASP II, CFDE I and CFDE III to verify the older Appleman scheme and the newer Tremblay scheme. **Table 6** shows a summary of that forecast verification for a 1.5 km scale, for a forecast time near 12 hours, using Hit Rate (HR), False Alarm Rate (FAR) and True Skill Statistics (TSS). The HR (FAR) can be interpreted as the proportion of observed (not observed) events that were correctly (incorrectly) forecast. The TSS is the difference between the HR and the FAR. Ideally, one would like the HR to be 1, and the FAR to be 0. If the TSS is 1, then the forecast is perfect, while, if it is 0, there is no skill. **Table 6** indicates that the current forecast schemes have little skill, and considerable improvement is needed. Guan *et al*. (2001) showed that, if one examined the icing forecast for periods when the clouds were predicted correctly, then the icing forecast HR, FAR and TSS would improve to 0.63, 0.22, and 0.41 respectively. This analysis suggests that a major limitation in the current forecasts is our ability to correctly forecast cloud.

The work on improving icing forecasts is continuing. Tremblay *et al.* (1996b) have now proposed a new mixed-phase prognostic scheme, which improves the reality of the physical

Table 6.
A comparison of the Appleman and Tremblay icing forecast schemes with the Convair-580 data obtained during CASP II, CFDE I, and CFDE III.

	Hit Rate	**False Alarm Rate**	**True Skill Statistic**
Appleman			
CASP II	0.25	0.30	-0.05
CFDE I	0.26	0.20	0.06
CDFE III	0.18	0.13	0.06
Tremblay			
CASP II	0.28	0.31	-0.02
CFDE I	0.40	0.23	0.17
CFDE III	0.35	0.21	0.14

Figure 4.
A photo of the Convair-580 showing runback ice just aft of the heated leading edge of the wing for the severe icing episode of 16 February over Mirabel at -29ºC. Rime icing can be seen on the forward portion of the wing tip probe.

simulation with the forecast model. Such a scheme is currently being tested at CMC, for operational implementation in the near future, and tests similar to the above are being conducted to evaluate its improvement over past forecast algorithms.

The data from the AIRS project are still being analyzed, with the goal of improving real-time (< 6 hours) forecasts, near airports, using remote sensing instrumentation. It is hoped that, by using a combination of remote sensors (radars, microwave radiometers, etc.), surface-based sensors (precipitation type monitors, precipitation rate gauges, etc.), conventional satellite imagery, as well as high resolution numerical forecast models, improved forecasting techniques can be developed.

CONCLUSIONS

Many conclusions can be drawn from the data presented in this paper. A few highlights are listed here:

- Based on upper air soundings by rawinsondes, freezing precipitation at the surface often forms through a non-classical formation mechanism, without requiring the formation of ice particles and a melting layer;
- Approximately 80% of the SLD observed in-flight, near St. John’s and Ottawa, formed through the non-classical mechanism;
- Supercooled water can often co-exist with ice crystals, and the frequency of occurrence of such mixed phase cases was 25% of the time near St. John’s, and 49% of the time near Ottawa;
- As shown in **Table 4**, the cloud microphysical properties were quite different for the maritime project (CFDE I) than for the continental projects (CFDE I, CFDE III, and AIRS);
- Supercooled large drops (SLD) occurred 73% of the time during in-flight icing conditions experienced near St. John’s, and 41% of the time during in-flight icing conditions experienced near Ottawa;
- The FAR-25C envelopes were exceeded, with MedVD greater than 40 μm, approximately 20% (6%) of the time in-flight icing was encountered near St. John’s (Ottawa). This demonstrates that these potentially hazardous conditions occur quite frequently; and
- The current aircraft in-flight icing forecast schemes have low True Skill Scores (TSS), in part due to the problems involved in forecasting the occurrence of cloud.

The information obtained during CFDE/AIRS is also being used, in conjunction with other efforts in Europe and North America, to develop a climatology of the microphysical conditions related to icing around the world. This combined data set will be used by the regulatory agencies to evaluate whether a revision to FAR 25C is necessary, or whether separate information should be used to certify aircraft for flight into supercooled large drops. As was shown with the differences between the maritime conditions of CFDE I and the continental conditions of CFDE III/AIRS, it cannot be assumed that different locations, in other climates, will have the same icing conditions.

Already, the information obtained during CFDE/AIRS has been used to alert the regulatory agencies about the potential hazards due to freezing drizzle and freezing precipitation. Appropriate information has been transferred to pilots, and the aviation industry in general, about the problems involved.

Improved aircraft in-flight icing forecast techniques are being developed. It would be ideal to produce a forecast with cloud liquid water content and median volume diameter at each model grid point. Although parameterizations exist to estimate liquid water content, droplet size predictions are difficult. However, if such a technique could be developed, then it might be an objective method of showing the aviation community a weather forecast that could be used for all aircraft types and conditions. Unfortunately, the forecasts issued today contain vague terms, such as severe or moderate icing. What is severe for a single engine aircraft is probably light icing for a large jet passenger aircraft. Some common definitions that could be used by a pilot doing his flight planning, or deciding whether to avoid an area where icing has been reported, would be very useful.

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