



AIAA 2002-0674

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Observed During AIRS**

Stewart G. Cober and George A. Isaac
Cloud Physics Research Division
Meteorological Service of Canada
Downsview, Ontario, Canada

Thomas P. Ratvasky
NASA Glenn Research Centre
Cleveland, Ohio, U.S.A.

40th Aerospace Sciences Meeting & Exhibit
14-17 January 2002
Reno, Nevada

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ASSESSMENT OF AIRCRAFT ICING CONDITIONS OBSERVED DURING AIRS

Stewart G. Cober¹, George A. Isaac¹, and Thomas P. Ratvasky²

1. Cloud Physics Research Division, Meteorological Service of Canada, Downsview, Ontario, Canada

2. NASA Glenn Research Centre, Cleveland, Ohio, U.S.A.

ABSTRACT

In-situ measurements of aircraft icing environments have been made during 41 research flights conducted during the Alliance Icing Research Study (AIRS). A primary objective of AIRS was the collection of in-situ microphysics data in order to characterize aircraft icing environments, particularly those associated with supercooled large drops > 50 μm in diameter (SLD). There were 4175 30-s in-cloud observations at temperatures $\leq 0^\circ\text{C}$, of which 3355 contained supercooled liquid water, and therefore were assessed as icing environments. Of these, 2087 had ice crystal concentrations $< 1 \text{ L}^{-1}$, of which 576 contained SLD. The 99% liquid water content (LWC) was 0.45 g m^{-3} , while the 99% SLD LWC was 0.16 g m^{-3} . Comparisons are made to several common icing envelope formulations and other aircraft icing climatologies. The majority of the observations were made in stratiform winter clouds, and hence the data are compared to the Federal Airworthiness Regulation Chapter 25 Appendix C (FAR 25-C) envelopes for maximum continuous icing. There were 529 300-s in-cloud measurements at temperatures $\leq 0^\circ\text{C}$, of which 10 (1.9%) had LWC and droplet median volume diameter (MVD) values that were outside of the FAR 25-C curves. Approximately 1.5% of the 30-second in-icing observations were assessed as having LWC $> 0.2 \text{ g m}^{-3}$ and droplet median volume diameter (MVD) $> 30 \mu\text{m}$, and were considered hazardous following the methodology of Politovich (1996¹). There were 125 30-s measurements (4% of the in-icing cases) that were assessed as representing moderate or greater severity, following the potential accumulation curves from Newton (1978²). In general the AIRS data were quite similar to observations made in other recent field projects with one important distinction. The frequency of encountering hazardous icing or SLD conditions during AIRS was between 0.3 and 0.5 of the frequency during other field programs, depending on the hazard criteria being assessed.

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INTRODUCTION

Characterizing the aircraft icing environments associated with supercooled large drops (SLD) $> 50 \mu\text{m}$ in diameter is an important research objective for the U.S. Federal Aviation Administration (FAA) and Transport Canada. The 1997 FAA Inflight Aircraft Icing Plan contains recommendations to consider a comprehensive redefinition of the current aircraft icing certification envelopes when sufficient information is available worldwide on SLD and other icing conditions.

While several reports have documented icing conditions associated with SLD (Sand et al. 1984³; Politovich 1989⁴; Pobanz et al. 1994⁵; Cober et al. 1996⁶; Bernstein et al. 1999⁷; Marwitz et al. 1996⁸; Ashenden and Marwitz 1998⁹), it was found to be difficult to combine these observations into a single data base because of differences in the instrumentation used for measuring liquid water content (LWC) and the SLD spectra, and because of differences in the analysis and reporting procedures (i.e. different averaging intervals, cloud thresholds, SLD definitions, etc.). In addition, the collective data were believed to be insufficient for allowing an accurate statistical analysis of extreme icing and SLD conditions. A consistent database could be used to characterize the aircraft icing environments associated with freezing precipitation or SLD following Jeck (1996¹⁰). Consequently, several field projects have recently been conducted to attempt to fulfil this aim including the Winter Icing and Storms Project (WISP) (Rasmussen et al. 1992¹¹), the First and Third Canadian Freezing Drizzle Experiments (CFDE I and III respectively) (Isaac et al. 2001¹²), the NASA Glenn winter icing projects (Miller et al. 1998¹³) and the Alliance Icing Research Study (AIRS) (Isaac et al. 2001¹⁴). Results from WISP and CFDE have been described by Politovich and Bernstein (2002¹⁵), and Cober et al. (2001¹⁶), respectively. The results from AIRS will be presented here. These will be compared to several icing envelope formulations including Politovich (1996¹), Jeck (1996¹⁰), Newton

(1978²), Ashenden and Marwitz (1998⁹) and FAR 25-C. In addition, the results will be compared to similar measurements from the CFDE icing climatology (Cober et al. 2001¹⁶).

AIRS PROJECT

AIRS was conducted between 29 November 1999 and 19 February 2000. The primary objectives of the project were 1) to improve our ability to remotely sense aircraft icing regions using satellite, aircraft or ground based systems; and 2) to obtain additional data to characterize the icing environment, particularly icing associated with SLD. AIRS was based from Ottawa Ontario, and the majority of research flights were conducted in the vicinity of Mirabel Quebec, where a variety of remote sensing instruments were located. The project has been described by Isaac et al. (2001¹⁴), who also presented four case studies describing some of the extreme icing environments encountered during AIRS.

AIRCRAFT AND INSTRUMENTATION

Data presented here were obtained from two of the research aircraft that were employed during AIRS. These include the National Research Council (NRC) Convair-580 aircraft, which was described in Isaac et al. (2001¹²), and the NASA Glenn Twin Otter aircraft, which was described in Miller et al. (1998¹³). Instrumentation for these aircraft has been described in Cober et al. (2001¹⁷), Miller et al. (1998¹³), and Isaac et al. (2001¹²). Cober et al. (2001¹⁷) provides an assessment of the capabilities of the instrumentation on the Convair-580. Each aircraft contained sufficient instrumentation to measure the necessary cloud microphysics parameters including temperature, liquid water content (LWC), total water content (TWC), and the sizes and concentrations of cloud drops, SLD, and ice crystals. The two aircraft had very similar instrumentation suites, including Particle Measuring System (PMS) King LWC Probes, Skytech Research Inc. Nevzorov LWC/TWC probes, PMS FSSP, PMS 2D-C or 2D-G instruments, and a Sensor Systems Goodrich Corporation Rosemount Icing Detector (RID). The commonality of instrumentation between the two aircraft allowed application of the same analysis methodology. In total there were 41 research flights including 25 flights with the NRC Convair-580 aircraft, and 16 flights with the NASA Glenn Twin Otter aircraft. The total in-flight time was 111.3 hours, of which 38.4 hours (34%) were assessed to be in-cloud. The AIRS data reported here represent approximately 12,000 km of in-cloud data at temperatures $\leq 0^{\circ}\text{C}$.

DATA ANALYSIS

The analysis methodology is described in Cober et al. (2001¹⁶). The data were averaged over 30, 60, 120 and 300 second intervals. These represented horizontal length scales of approximately 3, 6, 12, and 30 km respectively for the Convair-580, and 2, 4, 8 and 20 km respectively for the Twin Otter. For each interval, data from the FSSP and 2D probes were combined to produce a normalized droplet spectrum at 1-micron resolution, from 1 micron to the maximum drop diameter observed (Cober et al. 2001¹⁶). Characteristics of the droplet spectrum such as LWC and median volume diameter (MVD) could then be determined. The phases of each in-cloud observation were assessed as liquid, mixed or glaciated following Cober et al. (2001¹⁷). Liquid-phase implies that there were no or a minimal number of ice crystals observed, with a maximum ice crystal concentration of less than approximately 0.1 L^{-1} . Glaciated-phase implies that no supercooled liquid water content (SLWC) was detected with any of the measuring instruments, which implies that any $\text{SLWC} < 0.01 \text{ g m}^{-3}$ (Cober et al. 2001¹⁷). Mixed-phase implies that both SLWC and ice crystals were observed with the instruments. Errors in assessing cloud-phase are described in Cober et al. (2001¹⁷).

In total, there were 13,357 in-flight data points measured at 30-s resolution with the Convair-580 and Twin Otter research aircraft. Of these, 4175 were assessed as being in-cloud at temperatures $\leq 0^{\circ}\text{C}$. Of these, 3355 contained SLWC, with 2087 having SLWC and ice crystal concentrations $< 1 \text{ L}^{-1}$. It is important to identify data with ice crystal concentrations $< 1 \text{ L}^{-1}$, because higher concentrations of ice crystals cause significant contamination of the FSSP measurements of the droplet spectra. In these cases, the droplet spectra cannot be accurately measured for drops larger than approximately $35 \mu\text{m}$ in diameter. Hence drop spectra were only determined for the 2087 cases where the ice crystal concentrations $< 1 \text{ L}^{-1}$. There were 576 liquid and mixed-phase SLD conditions, with temperatures $\leq 0^{\circ}\text{C}$, ice crystal concentrations $< 1 \text{ L}^{-1}$ and drops $> 50 \mu\text{m}$ in diameter.

RESULTS

a. Assessing the drop spectra LWC

To assess the quality of the data, the LWC determined from each drop spectrum was compared to the measured LWC using the Nevzorov LWC/TWC probe. A comparison between the measured LWC and integrated

spectra LWC is shown in Figure 1 for liquid and mixed-phase cases with ice crystal concentrations $< 1 \text{ L}^{-1}$. The 1:1 correlation is also shown along with $\pm 43\%$ error bars. The error estimates were determined assuming a $\pm 40\%$ error on the LWC computed from the spectra and a $\pm 15\%$ error associated with the Nevzorov probe measurement (Korolev et al. 1998¹⁸). There is a good agreement between the data, with 95% of the data points with TWC $> 0.1 \text{ g m}^{-3}$ agreeing within the $\pm 43\%$ errors. Cases with MVD $> 40 \text{ }\mu\text{m}$ are shown separately in Figure 1. These cases also show good agreement between the computed and measured LWC values. Cober et al. (2001¹⁹) showed that the Rosemount Icing Detector (RID) was capable of estimating LWC within $\pm 50\%$, for temperature $< -4^\circ\text{C}$ and LWC values below the Ludlam limit. They also showed that the RID was capable of measuring LWC within $\pm 50\%$ for cases with high MVD. Figure 2 shows a comparison between the RID and integrated spectra LWC. The data show a reasonable agreement with 80% of the data with TWC $> 0.1 \text{ g m}^{-3}$ falling within $\pm 64\%$ errors. This is the expected error assuming 40% and 50% errors in the integrated spectra LWC and RID LWC respectively (Cober et al. 2001¹⁶). The good agreement between the measured LWC with the Nevzorov probe, RID LWC, and the integrated spectra LWC, within the errors expected for such a comparison, provides confidence in the measurements of the drop spectra and in the derived variables such as LWC and MVD.

b. Microphysics conditions

Cloud-phase was assessed for each 30-s in-cloud observation. The relative fractions of liquid, mixed and glaciated conditions observed during AIRS were 0.30, 0.50 and 0.20 respectively. There were significant differences in the phase frequencies for data collected with the two aircraft. The fractions of mixed and glaciated conditions were 0.52 and 0.25 respectively for the Convair-580 data, compared with 0.42 and 0.07 for the Twin Otter data. This was primarily a temperature effect, since the average in-cloud temperature was -9.3°C for the Convair data, versus -5.0°C for the Twin Otter data. Cober and Isaac (2002²⁰) showed that the frequency of mixed-phase conditions exceeded liquid-phase for all temperatures colder than -5°C . They also showed that the fraction of glaciated-phase conditions increased with decreasing temperature. The frequencies of liquid, mixed and glaciated-phase conditions observed in AIRS with the two aircraft are consistent with these trends. Figure 3 shows cumulative probability curves for temperature for AIRS for each aircraft, as well as for data collected during CFDE III. The comparison with the CFDE III data is interesting because CFDE III was conducted in

the same geographic region as AIRS, but during the winter of 1997-1998. Differences between the Convair-580 and Twin Otter measurements were caused by different flight methodologies, and by differences for when the data were collected. The Twin Otter measurements were only made in December 1999, while the Convair-580 data were collected from December 1999 through February 2000.

The Nevzorov LWC/TWC probe was used to measure the TWC for liquid, mixed and glaciated-phase conditions. Cumulative probability curves for TWC for each phase are shown in Figure 4. The median values of TWC were 0.13, 0.10 and 0.07 g m^{-3} for liquid, mixed and glaciated-phase respectively. Differences are primarily associated with temperature, with the mean temperatures for liquid, mixed and glaciated conditions being -5.7 , -8.2 and -11.9°C respectively. The decrease in TWC with temperature is consistent with the results of Cober and Isaac (2002²⁰) and with other observations. Figure 5 shows cumulative probability curves of LWC for liquid and mixed-phase conditions with temperatures $\leq 0^\circ\text{C}$ and liquid fractions > 0.9 . The data are segregated by aircraft and compared to data from CFDE III. The three curves are quite similar, although the AIRS data are slightly lower than the CFDE III data.

Cumulative probability curves of droplet concentration, for liquid and mixed-phase conditions with temperatures $\leq 0^\circ\text{C}$ and ice crystal concentrations $< 1 \text{ L}^{-1}$, are shown in Figure 6. The AIRS and CFDE III Convair-580 results are very similar, while the Twin Otter data show systematically lower droplet concentrations. This was likely caused by the different flight methodologies for the Twin Otter and Convair-580, and is not believed to be an instrumentation problem. The Twin Otter flew only during December 1999, and made measurements in only nine different meteorological situations, compared to 25 situations for the Convair-580, which were spread out over the December 1999 to February 2000 period. In addition, the Convair-580 generally flew flight patterns for remote sensing validation, versus characterization flight patterns for the Twin Otter. The former give a more random sample of cloud conditions than the latter.

Ice crystal concentrations were measured with PMS 2D-C and 2D-G probes. The first four channels were ignored because of sizing and concentration errors (Korolev et al. 1998²¹). This implied a minimum ice crystal size threshold of $125 \text{ }\mu\text{m}$ for the Convair-580 and $75 \text{ }\mu\text{m}$ for the Twin Otter measurements. Cumulative

probability curves for AIRS Convair-580 and Twin Otter measurements, and CFDE III Convair-580 measurements of ice crystal concentrations are shown in Figure 7. The curves are based on mixed and glaciated-phase conditions with temperatures $\leq 0^{\circ}\text{C}$ and ice crystal concentrations $> 0.3 \text{ L}^{-1}$. The median ice crystal concentrations were very similar for all three datasets, ranging between 3 and 5 L^{-1} .

Characteristic droplet, SLD and ice crystal spectra were determined by averaging the data collected during AIRS. The results are shown in Figure 8, segregated by aircraft. The liquid-SLD spectra were based on liquid-phase cases with temperatures $\leq 0^{\circ}\text{C}$ and ice crystal concentrations $< 1 \text{ L}^{-1}$. The ice crystal spectra were based on glaciated-phase cases with temperatures $\leq 0^{\circ}\text{C}$ and ice crystal concentrations > 0 for sizes $\geq 125 \mu\text{m}$. The average spectra for each particle type are very similar when comparing the Convair-580 and Twin Otter measurements. The similarity is, in part, caused by similar instrumentation suites for each aircraft, similar analysis methodologies, and because the aircraft were often deployed into similar meteorological situations.

c. Comparison to the FAR 25-C icing envelopes

The 300-s data are compared with the Federal Airworthiness Regulation Chapter 25 Appendix C (FAR 25-C²²) curves for maximum continuous icing in Figure 9. The FAR 25-C curves represented extreme or worst-case environments for horizontal lengths of approximately 33 km. The FAR 25-C curves represent 99.9 percentile combinations of temperature, LWC and MVD, however they do not extend to $\text{MVD} > 40 \mu\text{m}$. There were 1335 300-s in-flight observations, from which 529 were assessed as being in-cloud with a temperature $\leq 0^{\circ}\text{C}$, of which 9 cases were assessed as having SLWC with $\text{MVD} > 40 \mu\text{m}$, and 1 case had $\text{MVD} < 40 \mu\text{m}$ and a LWC that exceeded the FAR 25-C curves. The in-flight probability of exceeding the FAR 25-C curves was 0.7%, while the in-cloud probability of exceeding the curves was 1.9%. The AIRS data are consistent with the FAR 25-C curves for $\text{MVD} < 40 \mu\text{m}$. However, 1.7% of the in-cloud AIRS data had SLWC with an $\text{MVD} > 40 \mu\text{m}$, and hence exceeded the FAR 25-C curves. For the CFDE data reported by Cober et al. (2001¹⁶), 4.7% of the in-cloud measurements exceeded the FAR 25-C curves. The higher frequency observed during CFDE was possibly a consequence of the flight methodologies employed during the respective projects. Regardless, in both CFDE and AIRS, icing conditions with $\text{MVD} > 40 \mu\text{m}$, on a horizontal scale of 30 km, were encountered at frequencies higher than the FAR 25-C 99.9% curves.

d. Comparison to potential accumulation curves

The 30-second LWC and MVD data are compared with the potential accumulation curves suggested by Newton (1978²) in Figure 10. The data include liquid and mixed-phase conditions with $\text{TWC} > 0.005 \text{ g m}^{-3}$, temperature $\leq 0^{\circ}\text{C}$ and ice crystal concentrations $< 1 \text{ L}^{-1}$. Newton classified potential accumulations of 1, 6 and $12 \text{ g cm}^{-2} \text{ h}^{-1}$ as representative of light, moderate and severe icing conditions respectively. For each icing environment identified during AIRS the potential accumulation was determined, and a severity indicator was assigned following Newton (1978²). In summary, 61.1% of the in-icing data points had potential accumulations $\geq 1 \text{ g cm}^{-2} \text{ h}^{-1}$, 5.9% had potential accumulations $\geq 6 \text{ g cm}^{-2} \text{ h}^{-1}$ and 0.14% had potential accumulations $\geq 12 \text{ g cm}^{-2} \text{ h}^{-1}$. Potential accumulations of moderate or greater severity ($> 6 \text{ g cm}^{-2} \text{ h}^{-1}$) were observed 3.0% of the time in AIRS during flight in-cloud at temperatures colder than 0°C , compared with 6.1% of the time during CFDE III.

The data in Figure 10 are also segregated by phase into liquid and mixed-phase conditions. There are no significant differences in the data for the liquid and mixed-phase cases with $\text{MVD} < 40 \mu\text{m}$ and $\text{LWC} < 0.4 \text{ g m}^{-3}$. Conversely, the majority of conditions with $\text{MVD} > 40 \mu\text{m}$ or $\text{LWC} > 0.4 \text{ g m}^{-3}$ were assessed as liquid-phase. These observations are consistent with the results of Cober and Isaac (2002²⁰) who performed a similar analysis with a substantially larger data set. They suggested that coexisting SLD and ice crystals would experience high collision efficiencies, and possibly secondary ice crystal production, both of which would cause the SLD hydrometeors to freeze. Similarly, high LWC regions with ice crystals would likely result in the ice crystals growing rapidly by vapour deposition and riming, with the ice crystals reducing the available LWC.

e. Assessing Politovich hazardous conditions

The LWC and MVD were determined for each 30-s data point. Considering only cloud conditions with temperature $\leq 0^{\circ}\text{C}$ and ice crystal concentrations $< 1 \text{ L}^{-1}$, there were 38 observations with $\text{MVD} > 30 \mu\text{m}$ and $\text{LWC} > 0.2 \text{ g m}^{-3}$. These correspond to conditions that Politovich (1996¹) described as having the greatest detrimental effects on aircraft performance. This represents 6.6% of the observed SLD conditions, 0.9% of the observed in-cloud conditions, or 0.3% of the in-flight observations. All of these environments were associated with SLD formed through a condensation and collision-coalescence mechanism. These results are quite similar to

the CFDE results reported by Cober et al. (2001¹⁶). They found that 4.8% of the observed SLD conditions met the Politovich criteria when the SLD formed through a condensation and collision-coalescence mechanism.

f. Assessing 98% LWC and MVD curves

The FAR 25-C curves represent 99.9% probability curves for the combination of LWC, MVD and temperature values, for data collected at a constant horizontal averaging scale. A similar analysis was applied to the 2087 AIRS 30-second liquid and mixed-phase icing conditions with temperatures $\leq 0^{\circ}\text{C}$. Note that the AIRS data were not further segregated by temperature, and represent a shorter horizontal extent than the FAR 25-C data. For all temperatures $\leq 0^{\circ}\text{C}$, the data were segregated by increasing MVD, into bins of 100 data points. For each bin, the average MVD and 98% LWC values were determined. The results are shown in Figure 11, and are compared to the Newton (1978²) potential accumulation envelopes and the FAR 25-C curves for 0, -10 and -20°C . The error bars represent the MVD minimum to maximum range for each bin, and the 96 to 100% range of LWC values for each bin. A similar analysis for CFDE III data is shown for comparison, however the errors bars are not included for the CFDE III results. The AIRS and CFDE III results are quite similar, particularly for $\text{MVD} < 30 \mu\text{m}$. The CFDE data show a higher LWC peak near $30 \mu\text{m}$, and higher LWC values at $\text{MVD} > 400 \mu\text{m}$. These differences are likely caused by sampling different meteorological conditions; and variability because of a lack of sufficient data in a single field project. Very few SLD environments were measured during AIRS where the SLD formed through ice crystals melting in a warm layer and supercooling in a lower cold layer (classical freezing precipitation formation). Conversely, there were several flights conducted during CFDE III in classical freezing precipitation environments. The CFDE III data with $\text{MVD} > 400 \mu\text{m}$ were all observed in such environments, and hence the CFDE III results in Figure 11 for $\text{MVD} > 400 \mu\text{m}$ are probably more representative than the AIRS data. The AIRS and CFDE III results tend to follow the potential accumulation curve of approximately $10\text{-}12 \text{ g cm}^{-2} \text{ h}^{-1}$ for MVD from 30 to $300 \mu\text{m}$ and the potential accumulation curves of approximately $6\text{-}8 \text{ g cm}^{-2} \text{ h}^{-1}$ for $\text{MVD} > 30 \mu\text{m}$. For $\text{MVD} > 100 \mu\text{m}$, where the drop collision efficiency is approximately 1 and assuming that LWC is independent of MVD, the LWC-MVD data curves would be expected to be relatively flat. The trends in the AIRS and CFDE data are consistent with this hypothesis. With a larger data set, clear 99% curves could be derived. The data suggest that such curves would more closely approximate the

Newton potential accumulation curves than the FAR 25-C envelopes.

g. Assessing Jeck icing bins

The SLD data with temperatures $\leq 0^{\circ}\text{C}$, ice crystal concentrations $< 1 \text{ L}^{-1}$ and droplets $> 50 \mu\text{m}$, were used to compute the LWC percentiles following Jeck (1996¹⁰). The results are listed in Table 1. The mean LWC was 0.16 g m^{-3} , with a 99% LWC of 0.45 g m^{-3} . The 99% LWC for drops $> 50 \mu\text{m}$ was 0.16 g m^{-3} . These results are very similar to those observed during CFDE III (Cober et al. 2001¹⁶), with the AIRS results being systematically lower by approximately 20%.

Table 1. Percentiles of LWC for SLD Conditions

Range (μm)	Mean (g m^{-3})	50% (g m^{-3})	99% (g m^{-3})
1-50	0.13	0.12	0.44
50-100	0.009	0.004	0.06
100-200	0.009	0.0005	0.08
200-300	0.004	0	0.06
300-400	0.0007	0	0.01
400-500	0.0001	0	0.005
500-1000	0.0006	0	0.02
1000-1500	0.0004	0	0.02
1500-2000	0.0001	0	0
> 1	0.16	0.15	0.45
> 50	0.024	0.007	0.16
> 100	0.016	0.0005	0.15
> 500	0.001	0	0.04

h. Assessing Ashenden and Marwitz envelopes

Ashenden and Marwitz (1998⁹) used the 80% volume diameter (80VD) and the LWC to identify icing environments that caused the highest performance degradations on their Super King Air research aircraft, with $80\text{VD} \cdot \text{LWC}$ values between 10 and $100 \mu\text{m g m}^{-3}$ assessed as being the most hazardous. For the AIRS data, 22% of the SLD conditions met these criteria. This represented 3.5% of the in-cloud and 1.0% of the in-flight times. Ashenden and Marwitz also determined the number of encounters per hour for which the LWC incorporated in drizzle sized drops (44 to $194 \mu\text{m}$ in diameter) exceeded thresholds of 0.05 , 0.1 and 0.3 g m^{-3} . They determined the drizzle water content using a 1D probe in conditions where minimal ice crystal concentrations were observed. They also screened data with temperatures $> -1^{\circ}\text{C}$, and with significant mass in precipitation sized drops (i.e. freezing rain conditions). The AIRS data are compared to the envelopes derived by Ashenden and

Marwitz (1998⁹) in Figure 12. For the AIRS measurements, the LWC incorporated in drops $> 50 \mu\text{m}$ was used to represent the drizzle water content, and data with temperatures $> -1^\circ\text{C}$ were screened out. No attempts were made to exclude freezing rain conditions. Encounters per flight hour were determined by using the number of 30, 60, 120 and 300-s observations that exceeded the drizzle LWC thresholds, and the fact that there were 111 in-flight hours during AIRS. The AIRS data for drizzle LWC thresholds of 0.05 and 0.10 g m^{-3} are similar in shape to those of Ashenden and Marwitz (1998⁹), although the AIRS data show an encounter frequency that is significantly less than the Ashenden and Marwitz results. The data from CFDE III for LWC thresholds of 0.05 and 0.10 g m^{-3} are also shown in Figure 12, and these agree much more closely with the Ashenden and Marwitz results. This demonstrates one of the most significant differences between the AIRS and CFDE III results, namely that the frequency of encountering SLD with LWC in drops $> 50 \mu\text{m}$ of 0.05 g m^{-3} , in terms of the numbers of encounters per hour of flight, was approximately 2.7 times greater during CFDE III than during AIRS. Similarly, for a SLD LWC of 0.10 g m^{-3} , the frequency was 2.2 times greater in CFDE than in AIRS. Similar results were suggested by the FAR 25-C and potential accumulation comparisons. In each, the AIRS and CFDE III frequencies of occurrence of in-cloud icing environments that were outside of the envelopes were different by factors of 2 to 3. Different flight methodologies and meteorological situations must account for some of the differences between the two projects. Convair-580 flights conducted during CFDE III were focused on characterization, while those during AIRS were primarily focused on remote sensing validation. This would presumably weight the CFDE III frequencies of occurrence to higher values, since the SLD conditions were sampled for considerable periods of time once they were found. In addition, the mean colder temperatures and corresponding higher fractions of mixed and glaciated-phase conditions observed during AIRS could also partly explain the lower frequencies of occurrence during AIRS. Considering that both CFDE III and AIRS were conducted in the same geographical region during a December to February time period, the results demonstrate substantial variability in SLD climatologies between different field project data sets.

CONCLUSIONS

Measurements of icing environments were made during 41 research flights conducted during the Alliance Icing Research Study. In total, there were 2087 30-second averages obtained in liquid and mixed-

phase clouds with temperatures $\leq 0^\circ\text{C}$ and ice crystal concentrations $< 1 \text{ L}^{-1}$. Of these, 576 had SLD $> 50 \mu\text{m}$ in diameter. Most of the data were obtained in regions with regular air traffic, and the data is directly applicable to icing related issues currently being considered by several regulatory authorities such as the FAA and Transport Canada. The analysis has led to the following conclusions:

1) Integrated drop spectra were determined from FSSP and 2D probes. The derived LWCs agreed with the measured LWCs from both a Nevzorov LWC/TWC probe and Rosemount icing detector, within the errors expected from such comparisons. This provides confidence in the data analysis techniques for determining the integrated spectra.

2) Based on the 300-second averages, which had comparable length scales to the FAR 25-C curves for continuous maximum icing, the LWC and MVD data for icing conditions with $\text{MVD} < 40 \mu\text{m}$ are consistent with the FAR 25-C 99.9% probability envelopes. However, considering that 1.7% of all in-cloud data at temperatures colder than 0°C had SLWC with $\text{MVD} > 40 \mu\text{m}$, it is clear that the FAR 25-C curves do not adequately represent all natural icing environments within the 99.9% probability criteria.

3) Based on analysis of the 30-second averaged data, the frequency of observed hazardous icing conditions were assessed using several techniques. A LWC of 0.45 g m^{-3} represented the 99% value. For cases where drops $> 50 \mu\text{m}$ in diameter were observed, the 99% LWC for SLD sizes was 0.16 g m^{-3} . Potential accumulations of moderate or greater severity ($> 6 \text{ g cm}^{-2} \text{ h}^{-1}$) were observed 3.0% of the time in AIRS during flight in-cloud at temperatures colder than 0°C . Similarly, icing conditions with $\text{MVD} > 30 \mu\text{m}$ and $\text{LWC} > 0.2 \text{ g m}^{-3}$ were assessed in 0.9% of the in-cloud observations. These correspond to conditions that Politovich (1996¹) described as hazardous. Ashenden and Marwitz (1998⁹) showed that $\text{MVD} \cdot \text{LWC}$ values between 10 and $100 \mu\text{m g m}^{-3}$ were associated with the largest performance degradations for their aircraft. For the AIRS 30-s data, 3.5% of the in-cloud measurements met these criteria. Regardless of the classification scheme, it is clear from the AIRS data that potentially hazardous icing conditions associated with SLD were frequent enough that they should be considered by the regulatory authorities.

4) The frequency of occurrence of hazardous

icing environments observed during AIRS, as a percentage of in-cloud conditions, was found to be substantially less than for the CFDE III results. Such environments were observed between 0.3 and 0.5 times less frequently during AIRS than CFDE III, depending on the criteria for the hazardous conditions. It is suggested that differences in the flight methodologies employed during the two projects, and differences in the meteorological situations account for some of the differences between the two projects. In general, AIRS data were collected somewhat more randomly than the CFDE III data, which would lead to lower frequencies of occurrence of hazardous conditions. In addition, the AIRS data were collected at systematically colder temperatures, and contained a higher fraction of mixed and glaciated-phase conditions. This would also lead to a lower frequency of occurrence of hazardous conditions.

ACKNOWLEDGEMENTS

Canadian funding for this research was obtained from the Meteorological Service of Canada, the National Research Council, Transport Canada, and the Canadian National Search and Rescue Secretariat. U.S. funding was obtained from NASA Glenn, the Federal Aviation Administration, and Boeing Commercial Airplane Group.

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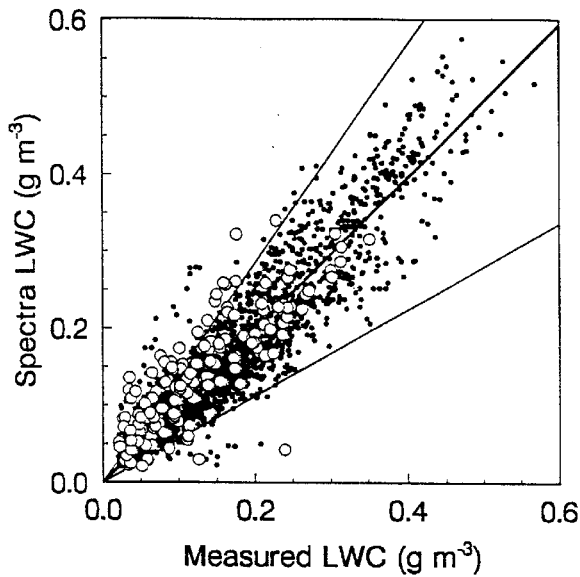


Figure 1. Scatter plot of LWC measured with the Nevzorov LWC/TWC probe versus the LWC computed from the drop spectrum for each 30-second measurement. The solid curves represent the 1:1 correlation and $\pm 43\%$ to the 1:1 correlation. The data include 2243 liquid and mixed-phase cases with ice crystal concentrations $< 1 \text{ L}^{-1}$. Open circles represent 171 cases with MVD $> 40 \mu\text{m}$.

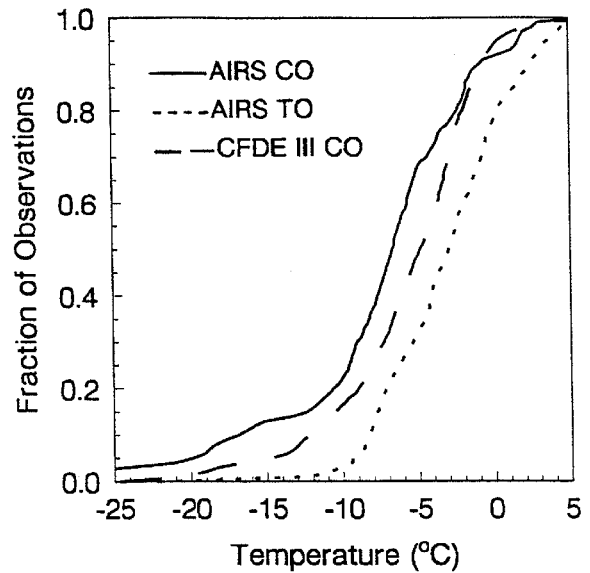


Figure 3. Cumulative probability curves of temperature for liquid and mixed-phase cloud conditions. The curves are based on 2498 AIRS Convair-580 (AIRS CO), 1359 AIRS Twin Otter (AIRS TO) and 4609 CFDE III Convair-580 30-second measurements.

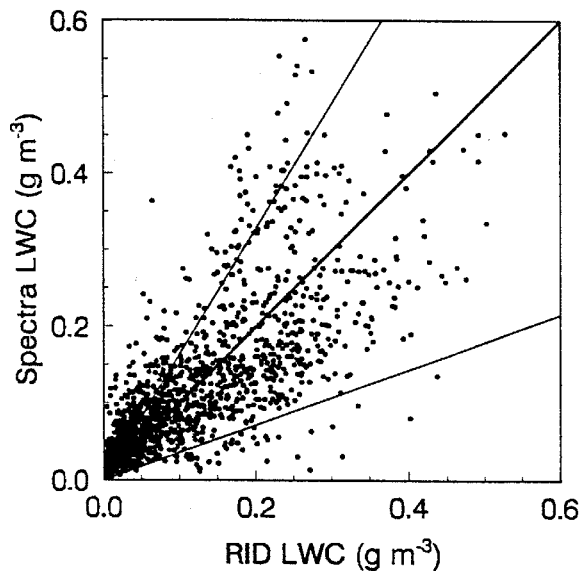


Figure 2. Scatter plot of LWC inferred from the Rosemount icing detector (RID) versus the LWC computed from the drop spectrum for each 30-second measurement. The data represent 1292 liquid and mixed-phase cases with temperatures $< -4^\circ\text{C}$ and ice crystal concentrations $< 1 \text{ L}^{-1}$. The solid curves represent a 1:1 correlation and $\pm 64\%$ to the 1:1 correlation.

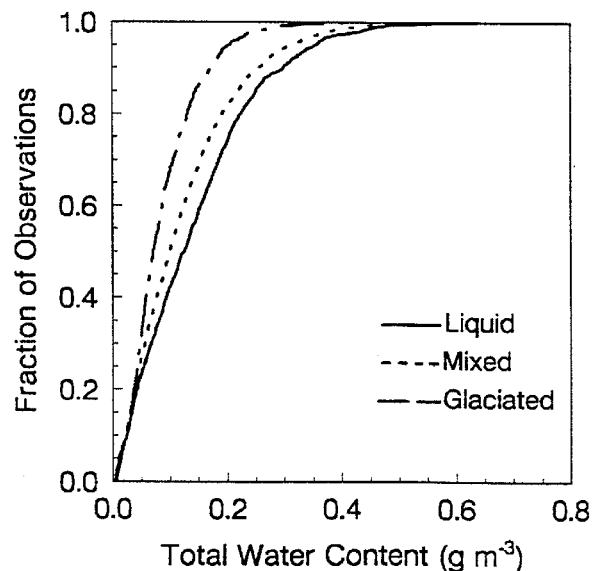


Figure 4. Cumulative probability curves of TWC as a function of cloud-phase, for AIRS 30-second cloud averages with TWC $> 0.005 \text{ g m}^{-3}$ and temperature $\leq 0^\circ\text{C}$. The data are based on 1278, 2060, and 808 liquid, mixed and glaciated-phase cases respectively.

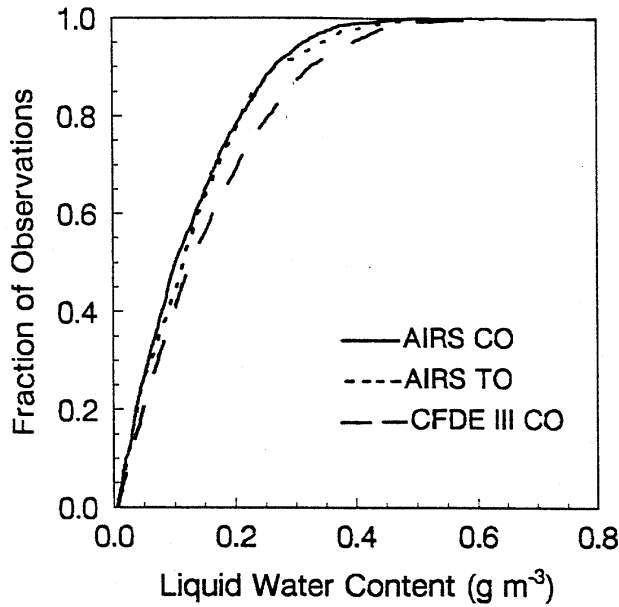


Figure 5. Cumulative probability curves of LWC for liquid and mixed-phase cases, with TWC > 0.005 g m⁻³, temperature ≤ 0°C, and liquid water fraction > 0.9. The data are based on 1606 AIRS Convair-580, 940 AIRS Twin Otter and 3309 CFDE III Convair-580 30-second measurements.

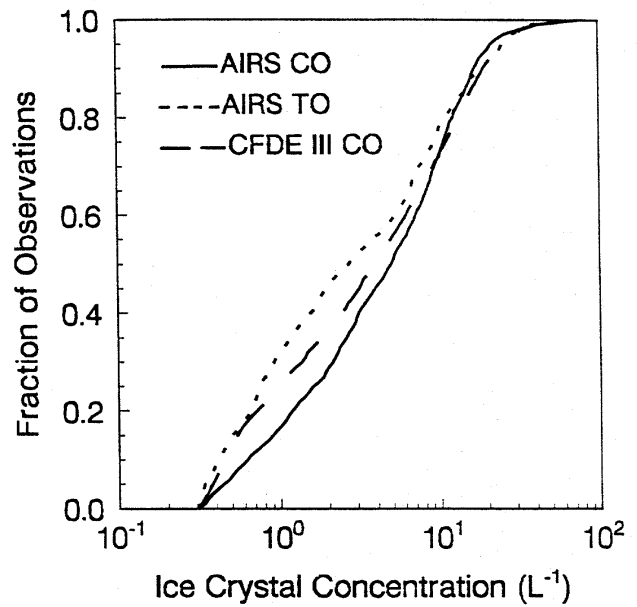


Figure 7. Cumulative probability curves of ice crystal concentration for mixed and glaciated-phase cloud conditions. The data include only cases with temperature ≤ 0°C and ice crystal concentrations > 0.3 L⁻¹. The curves are based on 2035 AIRS Convair-580, 420 AIRS Twin Otter and 2310 CFDE III Convair-580 30-second measurements.

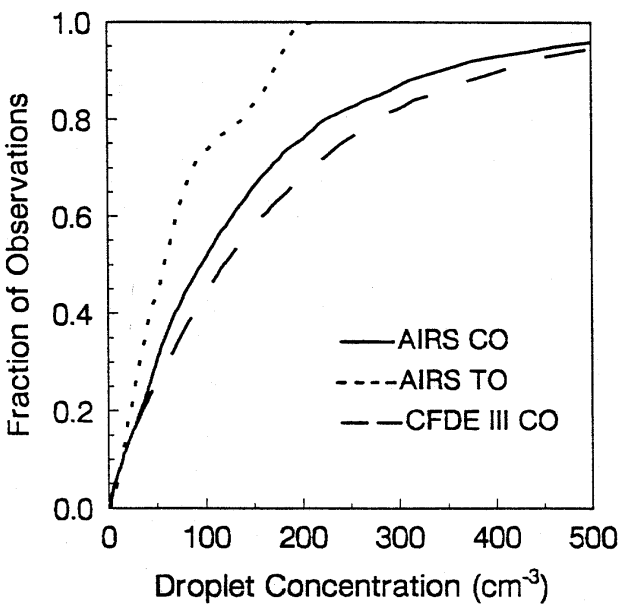


Figure 6. Cumulative probability curves of droplet concentration for liquid and mixed-phase cloud conditions with temperature ≤ 0°C. The curves are based on 2291 AIRS Convair-580, 1064 AIRS Twin Otter and 4335 CFDE III Convair-580 30-second measurements.

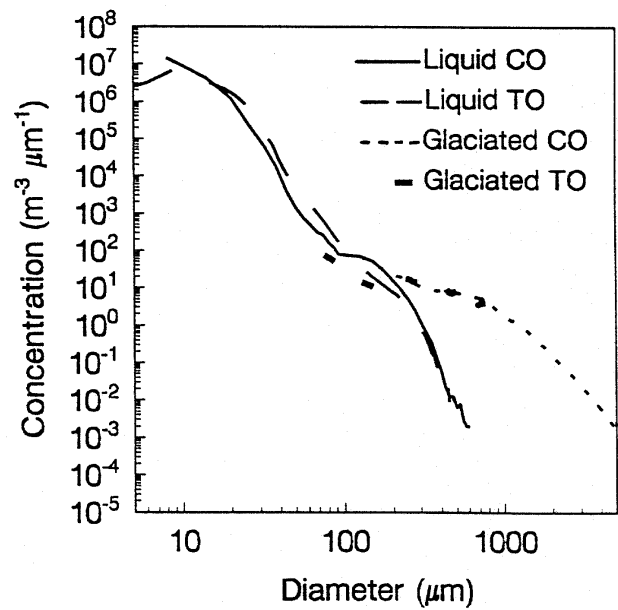


Figure 8. Average drop, SLD, and ice crystal spectra observed with the Convair-580 (CO) and Twin Otter (TO) during AIRS for cloud conditions with temperature ≤ 0°C, TWC > 0.005 g m⁻³. The drop and SLD spectra are based on liquid-phase conditions with ice crystal concentrations < 1 L⁻¹. The ice crystal spectra are based on glaciated-phase conditions.

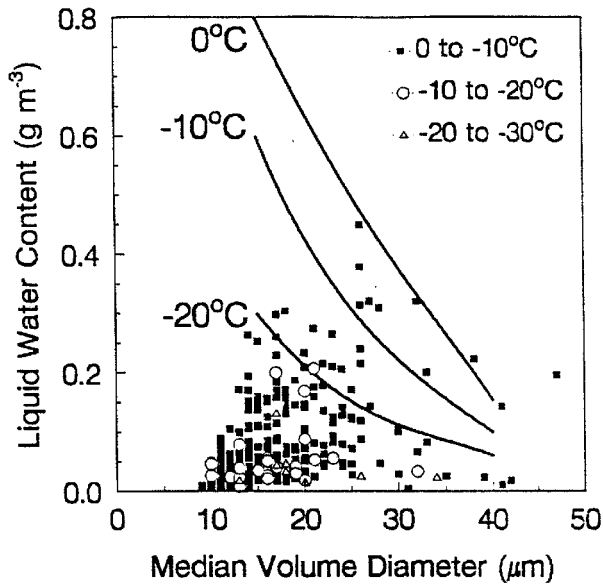


Figure 9. Plot of MVD versus LWC for 300-s averaged data. The MVD is determined from the integrated drop spectra, while the LWC is determined from the Nevzorov LWC/TWC probe measurements. The data represent Convair-580 and Twin Otter liquid-phase cases with $T_a \leq 0^\circ\text{C}$ and ice crystal concentration $< 1 \text{ L}^{-1}$. The solid curves represent the FAR 25-C envelopes for 0, -10 and -20°C .

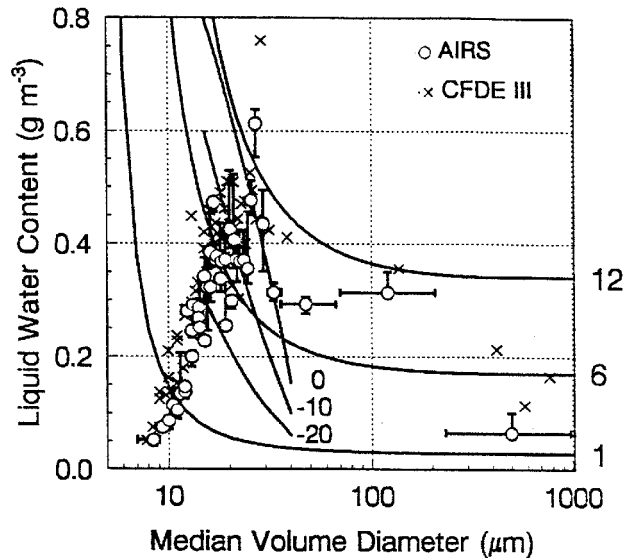


Figure 11. Plot of MVD versus LWC for AIRS liquid and mixed-phase cases with temperature $\leq 0^\circ\text{C}$ and ice crystal concentration $< 1 \text{ L}^{-1}$. The data were segregated by MVD into bins of 100 data points. Each bin data point shows the average MVD for the bin, along with a range from the maximum to the minimum MVD, versus the 98% LWC value, along with a range from the 96-100% LWC values. Similar analysis from CFDE III is shown for comparison.

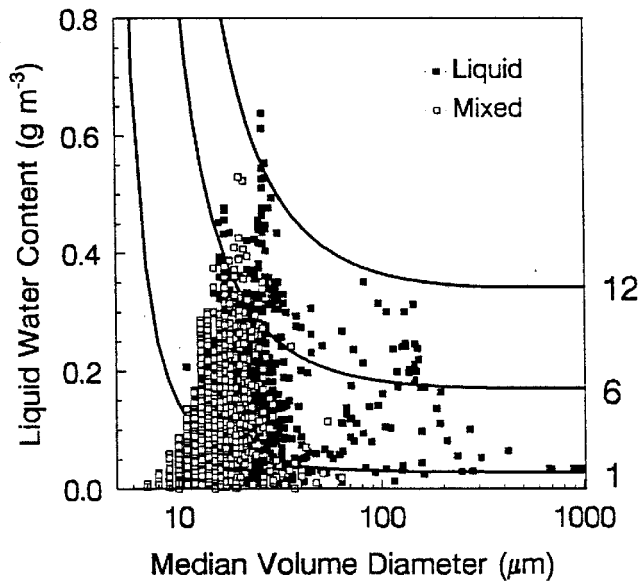


Figure 10. Plot of MVD versus LWC for 30-s averaged data collected with the Convair-580 and Twin Otter during AIRS. The data represent 1198 liquid and 881 mixed-phase cases with temperature $\leq 0^\circ\text{C}$, $\text{TWC} > 0.005 \text{ g m}^{-3}$ and ice crystal concentration $< 1 \text{ L}^{-1}$. The solid curves represent potential accumulation curves for 1, 6 and $12 \text{ g cm}^{-2} \text{ h}^{-1}$, as defined by Newton (1978²).

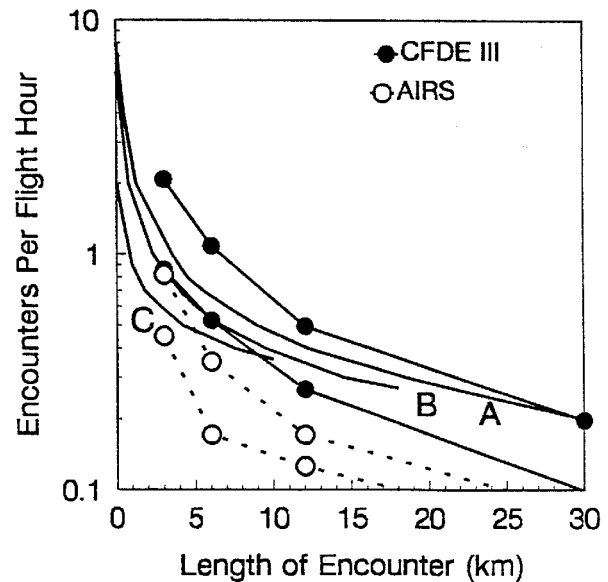


Figure 12. Plot of encounter length versus encounters per flight hour for SLD conditions. The curves A, B and C represent the results of Ashenden and Marwitz (1998³) for drizzle LWC thresholds of 0.05, 0.10 and 0.30 g m^{-3} respectively. The other curves represent analysis of the AIRS and CFDE III observations for SLD LWC thresholds of 0.05 and 0.10 g m^{-3} .