8.4 SCALES OF AIRCRAFT ICING: A COMPARISON OF ICING PIREPS TO LIQUID WATER MEASUREMENTS FROM RESEARCH AIRCRAFT

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1. Introduction

Icing severity, as reported by pilots, is a subjective measure of how adversely an aircraft is affected by a variety of parameters. These parameters include the existing icing conditions (i.e. liquid water content, temperature, and drop size), the type of aircraft and its icing protection measures, the way that the aircraft encounters the icing conditions, and the experience and perception of the pilot. The interaction of these can be very complex and highly variable (Sand and Biter 1993).

Research aircraft provide an objective measure of the temperature, liquid water content, and drop sizes present at a specific location and time. Comparing these measurements with pilot reports (PIREPs) of icing made nearby in space and time can provide an indication of how well subjective pilot reported severity relates to the measured conditions. High amounts of supercooled liquid water (SLW) can result in high accretion rates of ice on an aircraft, which leads to an increase in the expected icing severity (Politovich 2003). It would follow, then, that if an aircraft measures high (low) amounts of liquid water, then other aircraft in the vicinity should report more (less) severe icing.

2. Data

Aircraft data from a variety of platforms were compiled from flight programs over the continental U.S. (CONUS) and Canada between 1997 and 2004. All flights were made during the cool season (November – March), and deep convection was avoided for safety reasons. The sources of these data were the NASA Glenn Twin Otter, the National Research Council of Canada Convair 580, the University of North Dakota Citation, and a commercial aircraft doing certification tests. These aircraft flew on a total of 139 flight days during this time period and collected 397 hours of data – 47% of which were spent in icing conditions. Each aircraft was outfitted with a CSIRO liquid water content probe (King et. al 1978). CSIRO probe observations were corrected for any biases and combined with subfreezing temperature measurements to determine when and how much SLW was present. Icing PIREPs were also collected for this time period, providing reported time, location, and severity of the icing or lack thereof.

3. Methodology

Matching up these datasets is not a trivial proposition. Although a PIREP is made for a specific time and location, the reported icing severity represents an accumulation over an unspecified distance and time. Without information on this aspect of a given PIREP, it must be treated as a point observation for this study. Research aircraft data, on the other hand, are continuously collected in one or ten second increments, which makes them quite noisy (see Fig. 1). Without any data smoothing, it would be possible for hundreds of aircraft data points to be matched to a single PIREP.

To provide a more reasonable assessment of the environmental conditions, the data need to be averaged or smoothed. Each aircraft sampled the

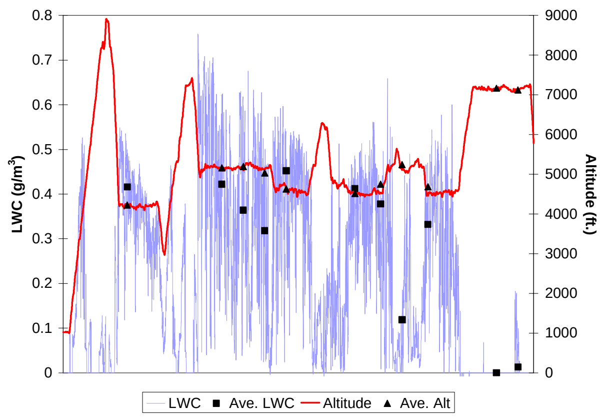

Figure 1. *One second values of CSIRO measured liquid water content (blue line) and altitude (red line). The black squares (LWC) and triangles (altitude) represent these fields after averaging and ignoring points where the altitude changed by more than 1000 ft over 20 km.*

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atmosphere at a different speed and changed speeds during the flights. Because of this, simple time averaging would result in rather inconsistent spatial coverage for each sample. Slower aircraft samples would represent a much shorter distance than those from a faster aircraft. To provide more consistent data, the observations were averaged over 20 km distance legs (black squares and triangles in Fig. 1). The number of one second measurements in each average point varies based on the speed of the aircraft (see Table 1). For example, the Twin Otter takes more than twice as long as the certification aircraft to cover a 20 km leg. The majority of the research aircraft dataset is comprised of Twin Otter observations (53%; Table 1). They also dominate the matched aircraft/PIREP dataset for the largest and smallest cylinders (discussed later), making up 80% and 88% of the data points, respectively (Table 1). The aircraft position was set to the average of the latitude, longitude, and altitude over the 20 km leg, and the time of the observation was set to that of the midpoint.

Aircraft	Typical speed (m/s)	20 km time (s)	# of 20 km pts	# matches large / small cylinders
Twin Otter	60	333	1615	2213 / 251
Convair	100	200	630	152 / 14
Citation	123	162	249	26 / 6
Certification	130	153	555	388 / 14

Table 1. *List of aircraft types used, their average speeds and times to travel 20 km, the number of averaged data points available, and the number of matched points for the largest and smallest cylinders. Note that multiple 20-km average points could be matched to the same PIREP.*

As the data were being averaged, other quality control measures were implemented. Data collected during taxi, takeoff, and landing were deemed unusable because of abnormal airflow through the probes at slow speeds, so any measurements collected at aircraft speeds less than 46 m/s (90 kt.) were not used in the calculation of the average data point. Also, if the aircraft changed altitude by more than 0.3 km (1000 ft) over the course of a 20-km leg then that point was thrown out. Icing conditions can change more quickly in the vertical than in the horizontal so data taken during a large altitude change may not be particularly consistent.

Next, the 20-km averaged research aircraft observations were matched to all PIREPs that occurred within a defined cylinder of airspace (Δx, Δz; see Fig. 2) and time window (Δt). The minimum (maximum) cylinder size was Δx = 50 (200) km. For both cylinders, Δz = 0.6 km (2000 ft.) and Δt = ±30 min from the time of the research aircraft point. PIREPs with multiple altitudes were matched if at least part of their range of altitudes overlapped the cylinder. For example, a PIREP that reported icing from 5000 ft to 6000 ft would be included if the research aircraft's average altitude was between 5000 – Δz and 6000 + Δz.

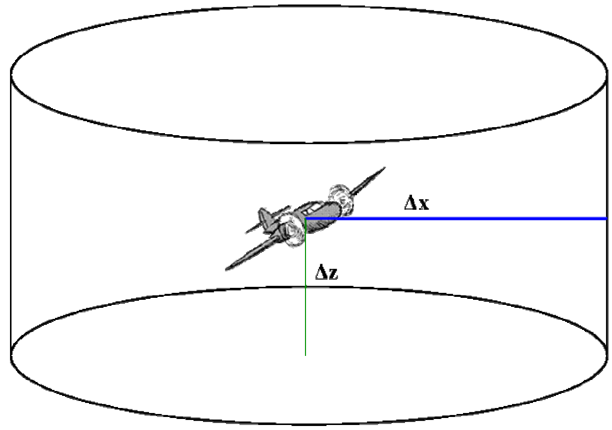

Figure 2. *Example of the cylinder centered on a research aircraft with a radius of Δx and a height of 2Δz. PIREPs inside this cylinder within a given time were matched to research aircraft data.*

Icing PIREPs are decoded into nine severity categories, with -1 representing no icing and 8 representing severe icing. The PIREPs for this study were divided into three groups: null (-1), light (1-3), and moderate or greater (MOG; 4+). For each of these groups the number of research aircraft SLW measurements that was matched to PIREPs in the group was counted. Multiple research aircraft measurements could be matched to a single PIREP. For example, it typically takes the Twin Otter 5 minutes to travel 20 km. If Δt = ±30 min and the Twin Otter remains within the specified Δx and Δz of the PIREP during this time then up to twelve 20-km average points could be matched to that particular PIREP.

The aircraft type is part of the PIREP and plays a role in the icing severity. For example, a commercial jet typically has heated leading edges and flies high enough to avoid icing conditions for long periods of time, often only briefly encountering them on climb or descent. Smaller aircraft, protected by de-icing boots, may spend much of their time at altitudes where icing is more common and may have longer exposures. Some of these aircraft don't have ice protection. These factors may result in a variety of reported severities from different aircraft encountering similar icing conditions. In this study, all PIREPs were treated the same regardless of aircraft type.

4. Results

The correlation between research aircraft measured SLW and pilot-reported severity was highly dependent on the radius of the cylinder. A variety of cylinder sizes was tried, and as the radius was decreased the correlation improved. Using the 50 km radius, there were only 288 matches. The percentage of MOG PIREPs increased with increasing SLW, while the percentage of Null PIREPs decreased. No Null PIREPs were found with SLW > 0.4 g/m^3 (Fig. 3a).

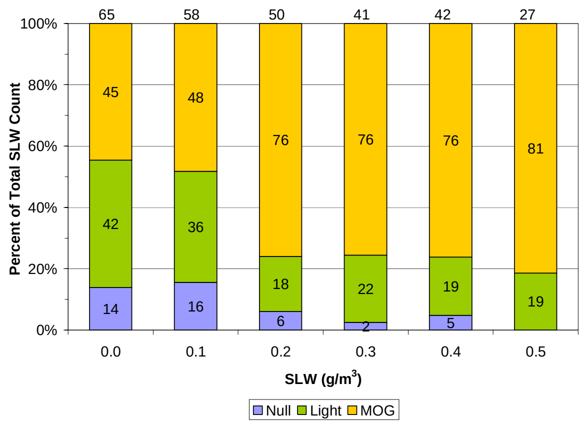

Figure 3a. Percentage of PIREP severity values that match each SLW bin for the smallest cylinder (Δx = 50 km, Δz = 0.6 km) and a Δt of 30 min. SLW values represent the maximum value in the bin. The values at the top of each bar represent the total data points in each SLW bin.

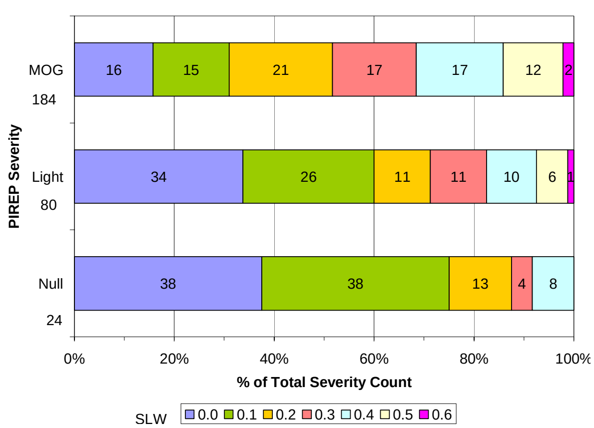

Figure 3b. As in Fig. 3a, but for the percentage of SLW values that match each PIREP severity. The value under each PIREP severity represents the number of data points for that severity.

These trends are expected, though the MOG percentages are fairly high even for the 0.0 – 0.2 g/m^3 SLW bins. Light PIREPs showed a trend similar to that of the Null PIREPs, with the highest percentages in the lowest SLW bins. However, unlike the Null PIREPs the percentage of light PIREPs remained fairly constant with increasing SLW, beyond 0.1.

The low percentage of Null PIREPs in the lowest SLW bin (0.0) is somewhat disturbing. This means that even if the research aircraft observed no SLW that icing was often reported nearby. As the radius increased so did the percentage of Null PIREPs associated with zero SLW, but it was still small (Fig 4a). One reason for this occurrence is the nature of the data collection effort. Almost all of the research aircraft flights used were flown with the purpose of finding and sampling icing conditions then climbing just above cloud to document the accreted ice shapes. The research aircraft would fly in an SLW-free environment

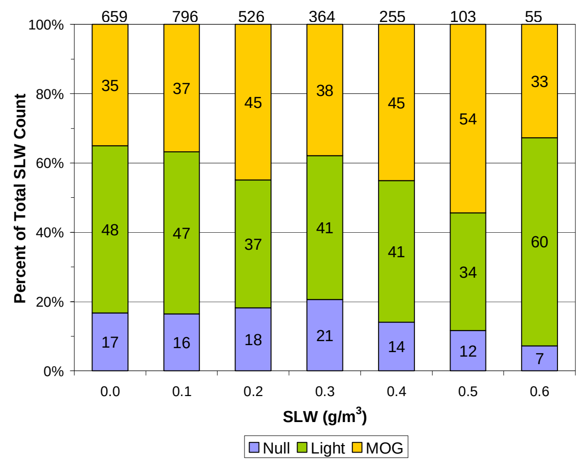

Figure 4a. As in Fig. 3a but for the largest cylinder (Δx = 200 km, Δz = 0.6 km).

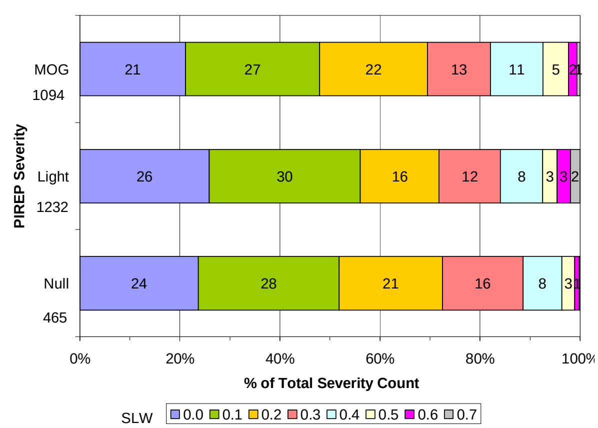

Figure 4b. As in Fig. 3b but for the largest cylinder (Δx = 200 km, Δz = 0.6 km).

while significant icing conditions were present just a few hundred feet below, where icing would be reported. This situation was common for the Twin Otter and the certification aircraft, which together made up 80 – 88% of the matched data points (see Table 1). The reverse situation also occurs (research aircraft in icing, with no icing just above), but null PIREPs are not as frequently given just above an icing layer. One way to mitigate this problem is to decrease the altitude difference allowable between the research aircraft and the PIREPs (Δz). This test was performed, but resulted in too few matches to draw meaningful conclusions, when a 50 km radius was used. If the research aircraft database can be expanded, such a test may be more feasible.

It is encouraging to note that the Null PIREPs all but disappear with increasing SLW. Also, as Fig. 3b shows, the majority (76%) of null PIREPs were matched with the two lowest SLW bins (< 0.1 g/m^3) compared with only 31% of MOG PIREPs. About half of the MOG PIREPs were associated with SLW > 0.2 g/m^3.

MOG icing PIREPs made up the largest percentage of all of the observations in each SLW bin (Fig. 3a), and they were also the most frequently reported in the vicinity of the research aircraft, making up 64% of the total PIREPs (Fig. 3b). Again, part of this can be attributed to the fact that the aircraft purposely tried to sample the worst icing conditions available. In more general PIREP analyses, MOG PIREPs represented a smaller portion of all icing PIREPs (39% in Brown et. al 1997).

When the largest cylinder dimensions were used for PIREP matching (see Sec. 3), a larger number of matches were found (2791), but there was very little relation between SLW and severity (Fig. 4). For this cylinder size, the percentage of null PIREPs actually increases slightly with increasing SLW up to 0.3 g/m^3 (Fig. 4a). The percentages of SLW values for each PIREP severity show little trend (Fig. 4b). Only the horizontal distance from the research aircraft was changed between the two tests, resulting in a near complete loss of correlation. Reducing Δz to 0.3 km (not shown) did nothing to help the correlation, nor did decreasing Δx from 200 km to 100 km. It appears that for a time range of 30 minutes the correlation is most dependent on the radius of the cylinder. It was also found that if the time range is shortened to 15 minutes then Δx can be increased from 50 km to 75 km, which results in a similar correlation. This implies that time may be as important as radius when examining icing conditions.

To help demonstrate why some PIREPs did or did not match research aircraft measured SLW values, two example cases from the dataset will be described.

5. Example Cases

a) January 31, 2001

On this day, there was a solid stratus deck over northeastern Ohio with cloud top temperatures between -10 and -15 °C (Fig. 5) and cloud top heights, as observed by the Twin Otter, between 6000 and 7000 ft. Stations throughout the area reported overcast skies with the ceilings around 2000 ft AGL. Some light rain and snow was falling at Canton-Akron (CAK) and Youngstown (YNG), but there were many reports of light and moderate icing in this area. NEXRAD radar showed some scattered areas of low reflectivity over Lake Erie, northeast of Cleveland (CLE). Based on these observations, fairly consistent icing conditions would be expected over northeast Ohio.

The Twin Otter took off from CLE, flew to the southeast and sampled the clouds between CAK and YNG, then returned to land at CLE, finding moderate amounts of SLW during the flight (Fig. 6). The colored parts of the flight track represent segments that were matched to specific PIREPs. The PIREPs are color coded to correspond to the segment to which they were matched. There was a very good correlation between PIREPs and

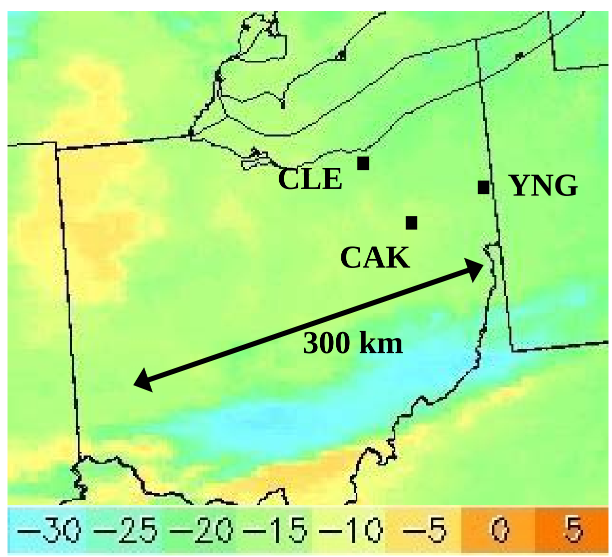

Figure 5. *Infrared satellite image from 31 January 2001 at 1445Z. Temperatures are in °C.*

aircraft measurements on this day. The segments with the highest SLW values (yellow, magenta, and dark blue) were nearest in space and time to the most intense PIREPs (five moderate and one light). Three of these were reported by the Twin Otter. The portion of the flight with relatively low SLW values (green) was matched to a PIREP of trace icing. The cyan section was matched to a light PIREP, and the average SLW values there were in between those of the other segments. All of these PIREPs were less than 50 km from the Twin Otter, which probably contributed to the good correlation. There was a portion of the flight during the return to CLE where no SLW was measured (red segment), and those data matched with a null icing PIREP nearly 200 km to the northwest. Though there was a great distance between the Twin Otter and the PIREP the altitudes were quite similar. Both were above the large scale icing cloud that extended from Ohio into southeastern Michigan (Fig. 5), where this PIREP was made.

b) November 19, 2003

On this day the NRC Convair 580 sampled some deep icing clouds over southeastern Ontario. Widespread, deep, cold-topped clouds and precipitation moved through the region in association with a vigorous upper level low. Light rain was reported throughout the region during the afternoon. Icing was present at upper levels, but only in small regions between precipitation areas, where relatively warm cloud tops were found. One such area of -15 to -20 °C cloud tops was evident from Kingston, Ontario (YGK) to west of Ottawa, Ontario (YOW; Fig. 7a) at 2015Z.

The two PIREPs near YGK (yellow markers; Fig. 8) were in or near the warm-topped clouds sampled by the Convair, and the aircraft measured only low SLW in this region. The PIREP in far northeastern NY (green marker) occurred later and was actually near another small region of embedded warm tops. At the time of this light PIREP the Convair was flying toward Montreal (YMX), within cold-topped clouds (Fig. 7b) that were dominated by ice crystals with low SLW content.

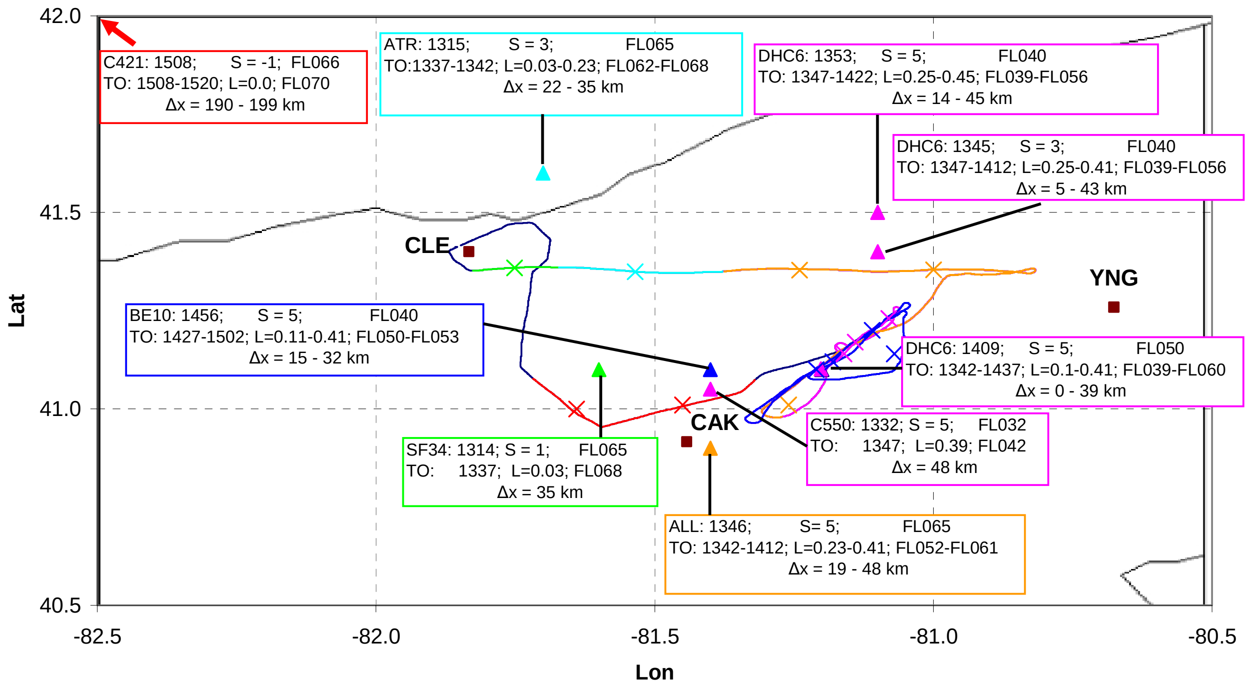

Figure 6. *Flight track and matched PIREPs for the Twin Otter flight on 31 January 2001. PIREP locations are marked with a colored triangle that corresponds with the colored flight segment that it was matched to. Each PIREP has a box with three lines. Line 1: PIREP aircraft type, time (UTC), icing severity, and flight level (100's of ft.). Line 2: research aircraft type (TO=Twin Otter, CO=Convair), time range over which it was matched to the PIREP, range of SLW, and range of levels. Line 3: range of Δx between the research aircraft and the PIREP for the flight segment. An X marks the midpoint of each 20 km segment. Takeoff and landing were at 1330Z and 1535Z, respectively.*

The icing conditions in this case were not very consistent. The highest amounts of SLW were found in the small areas where relatively warm cloud tops were exposed and all of the PIREPs occurred. The icing could accurately be classified as a small-scale phenomenon on this day. It is difficult to obtain a good correlation on such days because of the transient nature and small scales of the icing environment. The fact that the PIREP that best matched the observed SLW was also the one that was closest to the aircraft (light PIREP over YGK, reported by the Convair 580, matched with SLW values up to 0.2 g/m^3) further illustrates this point. By decreasing the radius the correlation would likely improve, even for a small-scale icing case.

6. Conclusions

The scale of icing conditions is an important concern when creating applications for the diagnosis and forecasting of icing and in the verification of gridded icing products. Icing conditions can change dramatically over very short distances (horizontally and vertically) and times. It is possible to have different water contents and reported icing severities within a small volume of airspace. Variations in icing conditions can occur in level flight as an aircraft passes through a strong gradient in cloud top temperature, radar reflectivity, etc. Research aircraft have documented such rapid changes on several occasions, but have also encountered cases of very consistent icing over long distances.

It is clear from this study that scale is an important issue in the forecasting of icing, as well as in the use of PIREPs. When possible, observations of icing-related conditions should be used in the context of the scales of the weather phenomena creating those conditions. Widespread, consistent, stratiform clouds allow a forecaster to apply icing observations over relatively large horizontal (but not vertical) distances and periods of time. Variability in observed conditions, such as in satellite imagery, implies that the icing is similarly likely to vary on smaller scales. In the absence of information on meteorological consistency (e.g. when doing objective verification), it is prudent to limit the length, height, and time scales over which observations are used. Assessing the spatial and temporal scales on which icing occurs provides better understanding of the meaning of the results from verification exercises, facilitates the improvement of existing icing products and allows for better use of PIREPs.

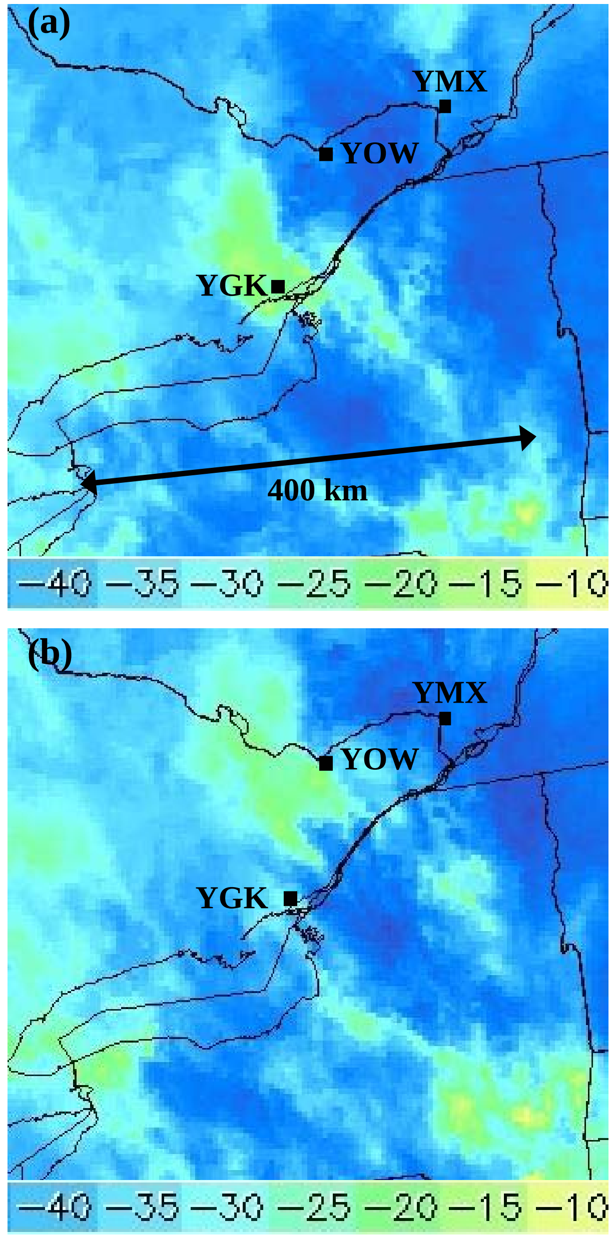

Figure 7. *As in Figure 5 but for 19 November 2003 at (a) 2015Z and (b) 2045Z.*

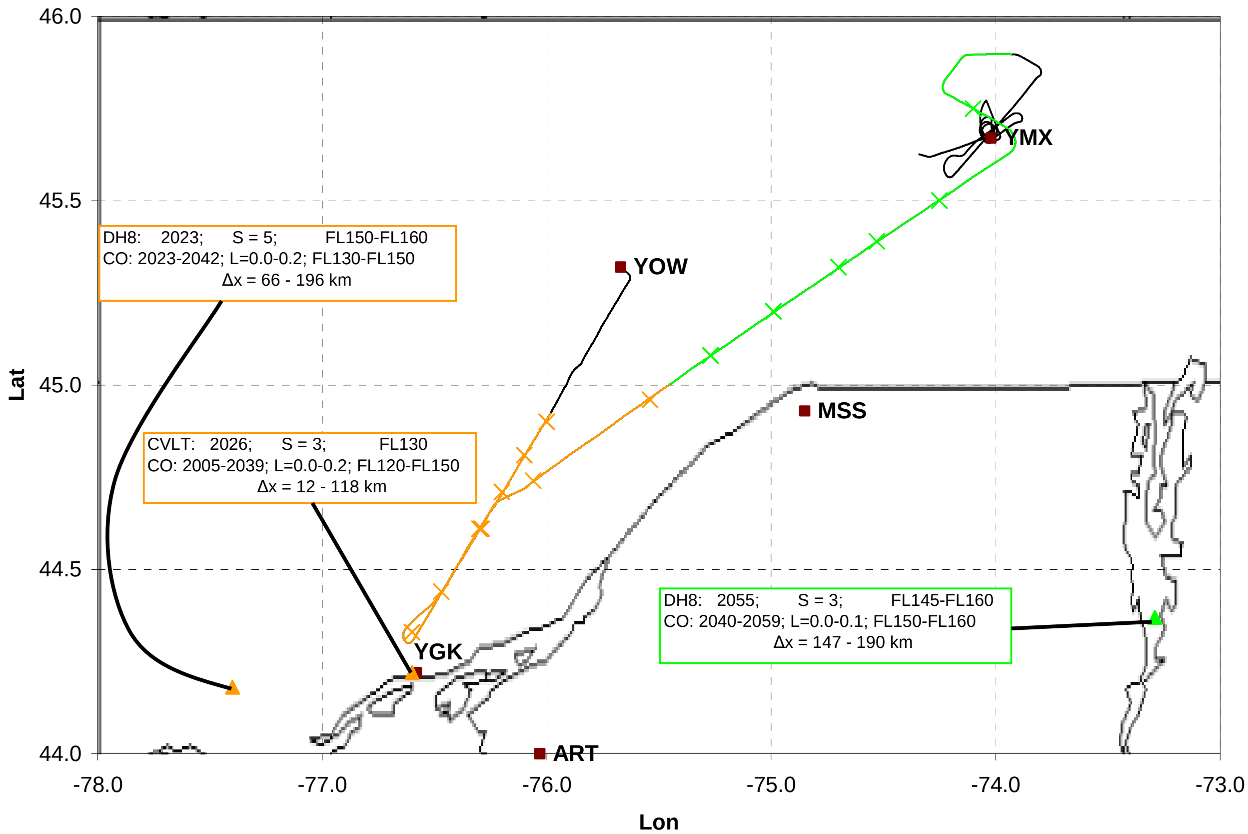

Figure 8. *As in Figure 6, but for a Convair 580 flight on 19 November 2003. Takeoff and landing were at 1933Z and 0005Z, respectively.*

7. References

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