ANALYSIS OF CAUSES OF ICING CONDITIONS WHICH CONTRIBUTED TO THE CRASH OF CONTINENTAL FLIGHT 3407

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1. INTRODUCTION

On February 12, 2009 at 10:20 pm EST, Continental Connection Flight 3407 from Newark to Buffalo crashed 5 miles short of the runway at Buffalo, killing all 49 people on board and one person on the ground. The National Transportation Safety Board (NTSB) is still investigating the crash, but preliminary reports show the airplane was experiencing icing conditions before the crash. Preliminary reports indicate that the pilot did not respond properly to the icing conditions, which contributed to the crash. However the presence of the icing conditions which were significant enough to cause aircraft problems needs further investigation to determine if pilots can be forewarned about these type of aircraft icing problems.

2. AIRCRAFT ICING

Aircraft icing occurs when aircraft fly through clouds with supercooled liquid water droplets. The droplets hit the airplane and then freeze onto the airplane. The buildup of ice on the wings and control surfaces disrupts the smooth air flow over the wings. The ice buildup increases drag, decreases lift and increases the stall speed, requiring additional thrust to maintain speed and altitude. If the aircraft's speed decreases below the stall speed, the aircraft can no longer stay airborne and could crash. Aircraft icing is generally classified as Rime Icing (which is caused by small cloud droplets freezing on contact giving a white frost like appearance), Clear Icing (which is caused by larger drizzle or rain droplets which splat when they hit causing a clear ice appearance), and Mixed (which is a combination of both types of droplets). The icing occurs on the leading edges of the wings, tail, etc. where the airflow separates. The air flow separation allows the droplets to continue straight on hitting the leading edges where it freezes on contact.

2.1 Aircraft Icing Protection

Flight 3407 used a Canadian designed Bombardier Q400 Dash 8 turboprop regional airliner. The Dash 8 is equipped with pneumatic boots on the leading edges of the wings, vertical tail fin, and the horizontal tail surfaces for deicing. The pneumatic de-icing boot consists of a rubber membrane that is filled with air, which when expanded, cracks any ice that builds up on the leading edges. The de-icing boots had been turned on before the airplane entered the clouds on descent into Buffalo.

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3. THE WEATHER AND CLOUDS

Overcast stratus clouds covered all of New York during the time of the flight. All surface observing stations in western New York reported light snow with surface temperatures around freezing. The NWS radars showed light precipitation covering most of western New York with intensities around 20 Dbz. An east-west oriented cold front was north of Lake Ontario. The cold front passed Buffalo around 06Z. Pilot reports of aircraft icing for the three hours prior to the flight showed light icing conditions in western New York. The Buffalo tower received no icing reports for the three hours prior to the crash. The controllers interviewed after the crash stated that receiving no icing reports did not necessarily mean there was no icing present, but that it was no worse than normal for the Buffalo area during this time of the winter. The NWS Aviation Weather Center had issued an AIRMET Zulu for icing which included western New York.

Figure 1 shows the IR satellite image for New England while Figure 2 shows a blowup of the western New York region with enhancements showing the 0 to -10 range (yellows), -10 to -20, and colder than -20 (blues) . The cloud top temperatures in western New York are -15 °C.

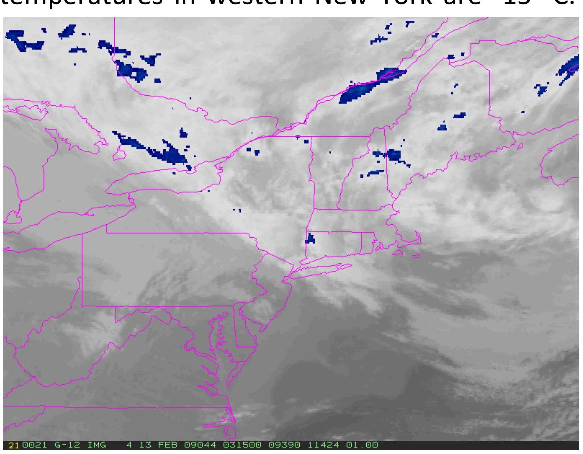

Figure 1. IR image 3:15Z

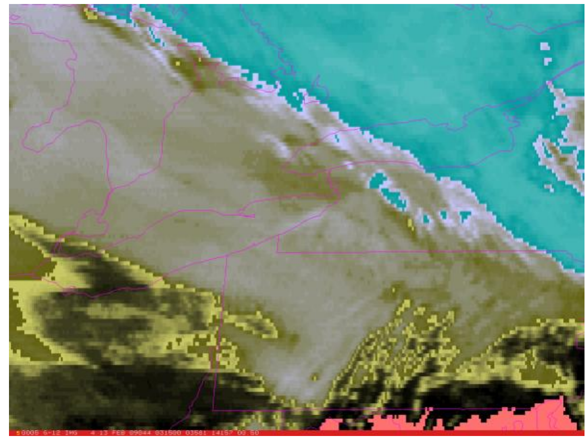

Figure 2 . Enhanced IR image of western New York at 3:15Z with 0 to -10 being the yellows, -10 to -20 being the browns, and colder than -20 °C being the blues.

The 0Z sounding from Buffalo is shown in figure 3. The digital listing of the sounding shows that the -15°C cloud top height was at approximately 11,000 ft. The 03Z surface observation from Buffalo showed an overcast cloud base of approximately 2,100 ft.

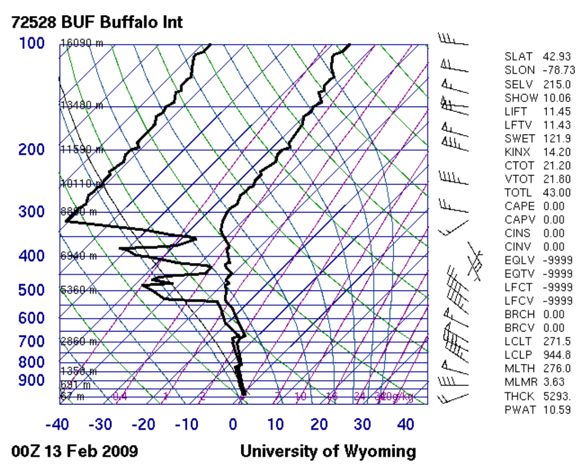

Figure 3. SkewT diagram of the 0Z sounding from Buffalo.

4. THE FLIGHT

Flight 3407 left Newark at 9:18 EST (2:18Z) and climbed to 16,000 ft. They flew above the clouds at 16,000 ft. until 9:57 EST (2:57Z) when they received permission to start their decent into Buffalo. At 10:05 EST (3:05Z) they reached 11,200 ft. and would have entered the clouds. Five minutes after entering the clouds the First Officer Rebecca Shaw said “Oh yeah, oh it’s a lot of ice”. At that time the aircraft was at 6,400 ft. Captain Marvin Renslow, who was flying the airplane, responded “Oh yeah, that’s the most I’ve seen, most ice I’ve seen on the leading edges in a long time. In a while, anyway, I should say”. They then talked for a couple of minutes about number of hours of flying. First Officer Shaw then said “I’ve never seen icing conditions. I’ve never deiced. ..I’ve never experienced any of that. I don’t want to have to experience that and make those kinds of calls. You know I’d’ve freaked out. I’d have, like, seen this much ice and thought, oh my gosh we are going to crash.” By this time the airplane was at 4,000 ft. The plane continued to descend and the crew prepared for a normal landing using the autopilot. The engines were slowed down, landing gear deployed, and the flaps were lowered when the plane reached 2,000 ft. The airplane autopilot then disconnected, the stall alarm went off, and the airplane started to go out of control. The pilot fought to regain control of the aircraft as it fell toward the ground during the next 20 seconds, but was unsuccessful.

The flight recording shows that the aircraft experienced a rapid buildup of ice within a 5 minute period, and that the crew was aware of the icing hazard. However they did not alter their flight procedures because of the icing conditions. The preliminary releases from the National Transportation Safety Board (NTSB) indicate that the accident investigation is concentrating on the pilot training rather than on the actual icing conditions.

Was this rapid buildup of ice unusual? The definition of aircraft icing intensity is as follows:

Trace: ice becomes perceptible. Rate of accumulation is slightly greater than the rate of sublimation.

Light: the rate of accumulation may require occasional use of deicing/anti-icing equipment to remove/prevent accumulation for flight in this environment for one hour.

Moderate: the rate of accumulation is such that frequent use of deicing/anti-icing equipment or flight diversion is necessary.

Severe: the rate of accumulation is such that deicing/anti-icing equipment fails to remove the accumulation of ice. Immediate flight diversion is necessary.

The pilot reports in western New York for the three hours prior to the crash were for light icing. Flight 3407 experienced icing conditions that would be classified as severe since their deicing equipment was turned on and within a ten-minute period the icing was sufficient to significantly impact the flying abilities of the aircraft. What would have caused these severe icing conditions for flight 3407, but not for other aircraft?

5. POSSIBLE CAUSES OF ICING

As air is cooled below the dewpoint temperature, droplets begin to condense. If an ice crystal condensation nucleus is present, an ice crystal will grow. Otherwise the droplet will remain liquid (within the temperature range of

0 to -40 C.). If there is a mixture of ice crystals and liquid water droplets within the cloud, the ice crystals tend to grow at the expense of the water droplets. The saturation vapor pressure over ice is less than the saturation vapor pressure over water which has the effect that water droplets will tend to evaporate while the ice crystals will grow. This is the classic Bergeron-Findeison process involved in precipitation formation. During time of the crash, light snow was reported at numerous locations in western New York, so ice crystals were available in the clouds. The depletion of liquid water content into ice water content can be quite rapid. Korokev and Mazin (2003) showed that liquid water can be converted to ice within a number of minutes if no new droplets are generated. Hence for icing conditions to be become hazardous, a continuing new source of liquid droplets is necessary. Vertical motions which continue to lift air parcel cooling them below their dewpoint temperature is the most common source of these liquid droplets. Korokev and Mazin (2003) showed that vertical motions as low as .01 m/sec are sufficient to continually regenerate the liquid droplets necessary to maintain a mixed environment of droplets and ice crystals.

An investigation of possible sources of vertical motions was done for this case. First several potential causes of vertical motion were eliminated. The precipitation pattern was downwind of Lake Erie, which appeared to be a case of lake effect snow. Lake effect snow is caused by cold air flowing across the warmer lake surface which results in an unstable temperature profile conducive to rising buoyant plume. However at the time of the crash, Lake Erie was primarily ice covered, and the sounding shown in figure 3 shows the temperature profile to be absolutely stable (air temperature decreasing with height more slowly than the moist adiabatic lapse rate). Hence upright convection does not appear to be a cause of the vertical motions.

Slantwise convection was also investigated as a possible source of vertical motion and also ruled out. Slantwise convection can occur in a baroclinic (strong horizontal temperature variation) situation similar to this case with the cold front to the north of Buffalo. As an air parcel moves horizontally into the colder air it is buoyant and rises creating the slantwise vertical motion. Cross sections were constructed of momentum and theta-e, but they failed to show any significant potential for slantwise convection.

In the Ohio valley there was a zonal jet core at 250 mb. The western New York area was in the left front quadrant of the jet, which generally is an area of upper level divergence and upward vertical motion. However the influence of the jet appears to be primarily limited to the upper level clouds, such as the higher clouds in northern and central New York shown in fig. 2.

The Buffalo 0Z sounding shown in figure 3 shows the winds at the surface from the west southwest at 20 knots veering to the west northwest at 50 knots at 850 mb. This veering wind profile is associated with warm advection and lifting. The prefrontal conditions represented by this sounding would have sufficient vertical motions to cause the stratus cloud mass covering western New York, the light precipitation, and the light aircraft icing conditions, but not necessarily the severe icing conditions encountered by Flight 3407.

Another potential source of vertical motions could be orographic lifting where the low-level winds encounter hills or mountains and are forced upward by the terrain. To investigate this possibility, we ran the WRF model over western New York using the RUC 0Z data as the initial conditions. The model was run at a 10 km resolution as well as a 6 km resolution. The results were nearly identical for both runs. Figure 4 shows the vertical motion contours at 850 mb (about 4,500 ft.) at 03 Z for the 10 km run. The straight line shows the path of Flight 3407. The red and blue contours are upward vertical motions. The yellow contours are downward vertical motions.

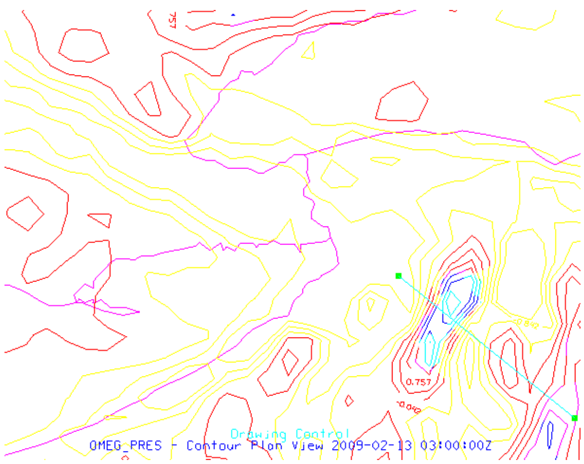

Figure 4. Vertical motion at 850 mb (approximately 4,500 ft.) at 3Z from the WRF model simulation. Straight line is path of Flight 3407.

The enhanced upward vertical motion in western New York was over enhanced terrain. The enhanced vertical motion was persistent in this area during the entire 3 hours of the model simulation. This was also the only area of enhanced vertical motions in western New York which would explain why other aircraft did not encounter the severe icing. If the upward vertical motion in a cloud is faster than the downward fall speed of the droplets, the cloud droplets will be swept upward toward the cloud top where the upward motion stops. This will cause an accumulation zone of liquid water near the cloud top, which can increase the liquid water content of the cloud. This accumulation zone of liquid water appears to be responsible for the rapid buildup of ice as Flight 3407 descended into the cloud.

6. CONCLUSIONS

Continental Flight 3407 from Newark to Buffalo during the evening of Feb. 12 crashed after encountering significant icing conditions. Within five minutes of entering the cloud on decent toward Buffalo, the crew commented on the rapid buildup of ice on the aircraft, and crashed within ten minutes of entering the cloud. Other aircraft in the general area were reporting only light icing conditions. An investigation into the possible causes of the icing conditions showed a small area of strong, persistent vertical motions caused by the wind interacting with the orography. These vertical motions could have caused an accumulation zone of liquid water. As Flight 3407 descended into the clouds, it flew through this zone of enhanced vertical motion, which would explain why it experienced severe icing conditions while other flights experienced only light icing.

An area for future development would be to incorporate the high resolution vertical motion information currently available in numerical models into icing diagnostic and forecast products.

7. REFERENCES

Korolev, Alexei V. and Ilia P. Mazin, 2003: Supersaturation of Water Vapor in Clouds. J. Atmos. Sci. , 60, 2957-2974.