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Aircraft-Specific In-flight Icing Forecasts

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1. INTRODUCTION

Aerodynamic icing studies show that different aircraft accumulate ice differently even in the same meteorological environment (Jeck 2001). In an obviously simple example, environmental air approaching an aircraft undergoes aerodynamic warming. If the aircraft is moving fast enough, air less than 0C may warm to greater than 0C and not let any cloud liquid water freeze on the aircraft surfaces. Because today's in-flight forecasts are one-size-fits-all, they do not serve the flying community well at all. We have developed and implemented better aircraft-specific icing forecasts at Schneider Electric.

Table 1. Aerodynamic and meteorological variables affecting aircraft icing

Body shape
Exposure time
Droplet size distribution
Chord length
Angle of attack
Flight speed
Liquid water content
Air temperature

Air temperature is just one of the variables that determine the way ice accumulates on an aircraft. These are listed in Table 1.

Engineers at the National Aeronautics and Space Administration (NASA) John H. Glenn Research Center have developed LEWICE (LEWis ICE accretion) software that evaluates the thermodynamics of super-cooled droplets as they impinge on a body given aerodynamic, flight, and atmospheric inputs then computes the resulting ice shape. Over the years they have added numerous abilities so the latest version, LEWICE 3.2.2 (Wright 2008), can accurately predict ice accretion in most meteorological conditions. LEWICE predicts ice shapes very well and has been extensively validated in conditions defined by Federal Aviation Administration (FAA) Regulation Title 14, Chapter 1, Part 25, Appendix C. In fact LEWICE software is the primary software that airplane manufacturers use to test their designs for certification of their aircraft to meet those regulations.

Aircraft icing is dangerous because it can cause a decrease in lift and/or an increase in drag. Icing is both reported and forecast subjectively based on definitions found in Table 2.

Two details in the definitions are apparent. First, each intensity is not defined by how much ice accumulates on the airframe but how quickly the ice accretes. Obviously, the longer the icing exposure, the more ice accumulates on the airframe. It is possible that,

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given enough time, an aircraft can collect as much ice in light conditions as it would in a short exposure to severe conditions. Therefore, the icing intensity definitions advise a pilot how quickly to respond to the icing threat.

Table 2. Airframe icing intensities

Trace - Ice becomes perceptible. The rate of accumulation is slightly greater than the rate of sublimation. It is not hazardous even though deicing/anti-icing equipment is not utilized, unless encountered for an extended period of time…over 1 hour.

Light - The rate of accumulation may create a problem if flight is prolonged in this environment (over 1 hour). Occasional use of deicing/anti-icing equipment removes/prevents accumulation. It does not present a problem if the deicing/anti-icing equipment is used.

Moderate - The rate of accumulation is such that even short encounters become potentially hazardous and the 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 reduce or control the hazard. Immediate flight diversion is necessary.

Second, the definitions point to aircraft performance losses as the criteria by which a particular intensity is reported or forecast. But these performance loss criteria are not defined and are very subjective.

Jeck (2001) suggested three ways to define icing intensities more objectively:

1) Liquid water content
2) Ice accretion rate
3) Icing effects on aircraft
    a) speed loss
    b) power increase
    c) rate-of-climb loss
    d) control loss
    e) vibration

The first only accounts for one of the Table 1 variables. At first glance, ice accretion rate seems like a workable metric, but it takes a much higher accretion rate to affect a larger aircraft, than it does a smaller one. Of the three only the third takes into account aircraft performance loss. Jeck outlined five aircraft responses to ice accumulation listed above. The final two are still subjective so are no better than current definitions. While the first is objective, speed loss only measures drag increases. In fact, if lift decreases, the aircraft will begin to fall even at a constant speed thus masking the performance penalty. Only power increase and rate-of-climb loss are truly objective. Realistically, rate-of-climb loss is difficult to measure; the pilot may not want to or be able to climb. This leaves power increase as the only practical option.

McCann and Kennedy (2000) and McCann (2004) explain how power increase is an ideal objective icing intensity metric. In level flight lift balances weight and is defined as

$$Lift = C_L A \frac{\rho V^2}{2},$$

where ρ is the air density, A is the cross sectional area of the aircraft component, V is the component's speed, and C_L is the lift coefficient. At constant speed, drag balances thrust and is similarly defined as

$$Drag = C_D A \frac{\rho V^2}{2},$$

where C_D is the drag coefficient. In order maintain altitude, the new thrust (power) is

$$Thrust_{iced} = Thrust_{clean} \frac{C_{L:clean}}{C_{L:iced}} \frac{C_{D:iced}}{C_{D:clean}}$$

where the subscripts *clean* and *iced* indicate conditions before and after ice accumulation, respectively. Thus, the power increase (PI) ratio is

$$PI = \frac{Thrust_{iced}}{Thrust_{clean}} = \frac{C_{L:clean}}{C_{L:iced}} \frac{C_{D:iced}}{C_{D:clean}}$$

Subtract one and multiply by 100, the PI ratio becomes the percent power increase (PPI) that a pilot would need to maintain level flight and constant speed.

This metric is completely objective and easily measurable. For example, the pilot of a light single-engine aircraft is in cruise flight with 20 inches of mercury (20" Hg) manifold pressure set. The plane encounters ice, and the ice starts to build up on the airframe. The pilot increases manifold pressure to 22" Hg in order to maintain altitude. The pilot has just encountered icing intensity of 10 PPI .

This is very simple for a pilot. There is no need to have special instrumentation. Since every aircraft has an engine power gauge, it also has a quantitative icing dial onboard.

PPI's flaw as a reporting metric is that it does not take into account de-icing or anti-icing efforts which probably will be the first action taken by the pilot to combat the icing.

However, as a forecast metric, it is meaningful to the pilot because it directly tells how the aircraft will respond to an expected ice accumulation. The pilot can also assess how dangerous the icing threat is. Flight into a forecast icing area may be possible if the aircraft has sufficient power reserves, and may be unadvisable if not.

The PPI measures iced aircraft performance at any ice accumulation. However, as mentioned earlier, icing intensity is a rate of accumulation, not how much. Therefore, McCann and Kennedy (2000) define icing intensity as the PPI in five minutes exposure.

If the PPI index is an ideal metric for quantifying icing effects, it is also aircraft dependent. Therefore, if the PPI index is to be truly useful, it must be computed for specific aircraft. Otherwise, it is no better than current practices. We illustrate such a product in this paper. First, we describe our method for computing PPI for specific aircraft which examines LEWICE output in computational fluid dynamics (CFD) software to obtain the iced lift and drag coefficients. The unpredictability of the results of our various aircraft analyses surprised us. We then show how we depict these results to users of our product.

2. COMPUTING PPI

Ice accumulation on aircraft surfaces depends on the aerodynamic and meteorological variables listed in Table 1. Our goal is to compute aircraft performance loss estimates on as many aircraft as possible in as many conditions as possible. Obviously, we have to simplify the process to achieve our goal. We decided that we would create relationships for the meteorological variables while fixing the aerodynamic variables. Since McCann (2004) showed that there is no straightforward relationship between the meteorological variables and PPI, we decided to create look-up tables for each aircraft type. These tables would span the expected air temperature, cloud liquid water, and droplet size spectra. Then we input the variables into LEWICE software to compute the resulting two-dimensional ice shape. We analyzed the ice shapes using computational fluid dynamics (CFD) software which solves the equations of motion for the resulting airflow.

We appreciate the multitude of potential aircraft types. The website http://aerospace.illinois.edu/m-selig/ads/aircraft.html has more than 1000 entries of airfoil shape usage for older aircraft. Unfortunately, the website has not been updated since 2010, so we continue to search for airfoil shapes for newer aircraft. In addition, numerous airfoil shapes are proprietary. Hopefully, we will be able to obtain those shapes from the manufacturers so that their aircraft will be in our database. We can eliminate many aircraft that are not certified for flying into icing. We are beginning with the most popular types, and we envision monitoring the requests from potential users to gauge the popularity of types not initially in our database. To date we have examined more than 50 specific aircraft representing more than 200 aircraft types. Aircraft /airfoil sizes range from the very small Lancair IV to the huge Airbus A380.

Airfoil shapes usually have names with prefixes which identify the designer and a number within the designer's catalogue. One of the most used designers is the National Advisory Committee for Aeronautics (NACA), the forerunner of NASA. Their numbering system describes the airfoil characteristics, for example NACA 23012 or NACA 64A109. We decipher the NACA number into an airfoil shape via decoding software. Many other airfoil shapes are in the website http://aerospace.illinois.edu/m-selig/ads/coord_database.html. Airfoil shapes are described in a table of (*x/c*, *y/c*) coordinates where *c* is the chord length. One must know the chord length to completely describe the airfoil.

Most aircraft have airfoil shapes which vary along the wing, typically thicker at the wing's root and thinner at its tip. We chose the tip shape as representative when given only those two shapes. In some cases the information identified a shape near the wing's middle which we chose as representative. Not only does an aircraft's airfoil shape vary, but also its chord length. We used the mean chord length when given, but more often we computed the mean chord length by dividing the total wing area by the wing span.

We assume the aircraft is flying at 10,000 feet altitude and at an airspeed of 2/3rds of its typical cruise speed rounded to the nearest 50 knots with a 250 knot maximum. We input the clean airfoil into the CFD software to determine the angle of attack at least two degrees with the lowest potential flow drag. We input the final clean airfoil information into the CFD software again to determine the actual clean lift and drag coefficients.

With the airfoil information LEWICE computes an ice shape with five minutes exposure time at various values of meteorological variables. The exposure time is short enough to reproduce the icing intensity definitions' spirit, but long enough to produce some meaningful ice accumulations.

We create numerous ice accumulation simulations modifying the meteorological variables for each aerodynamic configuration. The combinations of air temperature (T), cloud liquid water (LWC), and droplet size distributions (MVD) are infinite but can be limited by choosing representative values for each variable. For example, super-cooled LWC exists only in a finite range of air temperatures (0C to -40C). With temperatures less than about -20C ice shapes are similar because super-cooled drops freeze quickly. Similarly, LWC amounts rarely exceed 2 g m^{-3}. While most icing occurs with small droplet sizes, super-cooled large drops (SLD) pose a significant icing threat, so we must test ice shapes over a fairly large droplet size range. Intelligently limiting choices still leaves significant ranges of variables to analyze. We must select our representative values to ensure sufficient granularity yet limit the time necessary to create a PPI profile.

We varied T between -4C and -20C every 4C and included -30C. The input LWC values were 0.1, 0.2, 0.3, 0.4, 0.5, 0.75, 1.0, 1.5, and 2.0 g m^{-3}. The MVD were uniform at 20, 100, 300, and 900 µm. We limited the number of runs with MVD ≥ 100 µm to T ≥ -16C and to a minimum LWC which showed significant runback past .04*c* on the airfoil's upper side or past .08*c* on the airfoil's lower side. These are typical impingement limits of de-icing/anti-icing equipment (Hill et al. 2006). For each aircraft we ran LEWICE 60 times for MVD = 20 µm and as many as 96 additional times for the higher MVD values.

We use the LEWINT (American Kestrel Company, http://www.americankestrelco.com) interface to run LEWICE. LEWINT greatly simplifies the LEWICE setting-up process.

After each LEWICE run, we input the resulting iced airfoil coordinates into a two-dimensional CFD program, *Multielement Airfoils*, developed by Hanley Innovations, Inc. (http://www.hanleyinnovations.com/). The program solves the Euler equations of motion iteratively on a grid surrounding the airfoil. The grid points are denser nearer the airfoil to where they become extremely close to each other in order to resolve airfoil boundary layer effects. Figure 1 shows a sample grid.

Multielement Airfoils has numerous grid and analysis options. We have chosen grid densities of 20,000-100,000 grid points depending on airfoil size, and we iterate 3000 times for each run. There are many output options, but we only need the lift and drag coefficients to compute PPI.

Figures 2 and 3 show sample output from our analysis process.

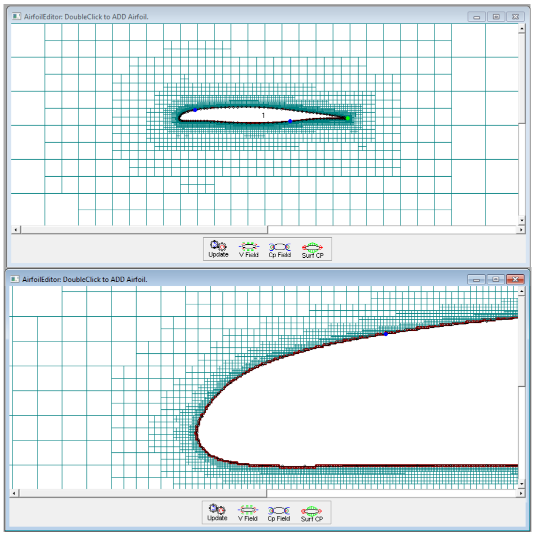


Figure 1. Two zoomed views of the grid generated by *Multielement Airfoils* for an iced Fokker100 airfoil.

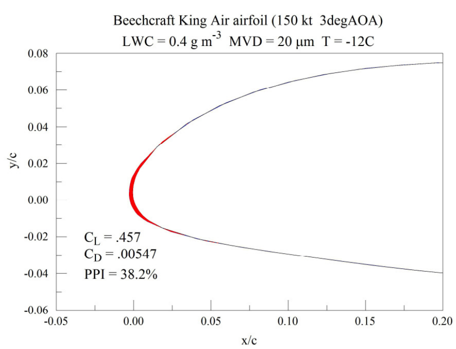


Figure 2. Ice (red) accumulation from the LEWICE program on a Beechcraft King Air airfoil using the inputs in the figure. The resulting performance change is in the lower left.

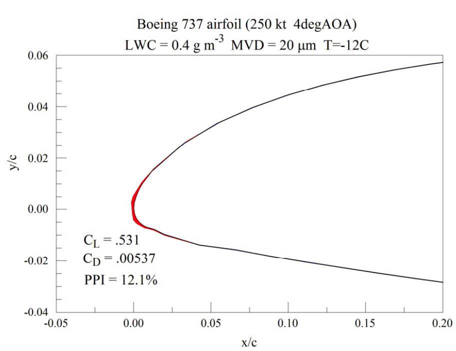


Figure 3. Same as Figure 2 for a Boeing 737 airfoil.

3. PPI ANALYSIS RESULTS

After analyzing only a few airfoils, we concluded that there are very few generalizations that we could make.

It is popular to think that larger aircraft are affected by ice less than smaller aircraft, but that is not always the case. Table 3 shows the aerodynamic characteristics of four different aircraft. These four aircraft represent four size classes, small, medium, large, and extra-large that we designate by the aircraft maximum take-off weight.

Figure 4 shows the PPI values for the four different airfoils in the atmospheric conditions given in the figure. While the three largest airfoils sort by size in this way, the small PA46 airfoil shows a similar PPI to the extra-large A320.

Figure 5 shows another PPI comparison of the four airfoils for a cooler and less moist airmass. In these conditions the three smaller aircraft show similar PPI values, but compared to Figure 4, the PA46 PPI is larger, and the BE20 and the AT72 PPIs are smaller. The extra-large A320 shows a small PPI comparable to Figure 4's. In fact, throughout most of the ranges of atmospheric variables, the A320 is not susceptible much to icing. The BE20 is the most vulnerable, and second is the AT72. The PA46 has some dangerous conditions, but other conditions hardly affect it.

These two figures illustrate that an aircraft's performance loss from icing is a complex relationship of both meteorological and aerodynamic variables. There is no simple

Table 3. **Aerodynamic characteristics of four aircraft in LEWICE experiments**

Aircraft Type	Airfoil shape	Mean chord	Angle of attack	Speed
Piper Malibu (PA46)	NACA 23009	1.24 m	2°	150 kt
Beechcraft King Air (BE20)	NACA 23012	1.69 m	3°	150 kt
ATR 72 (AT72)	NACA 43013	2.21 m	3°	200 kt
Airbus A320	Airbus	3.59 m	2°	250 kt

Table 4. PPI(/100) look-up table for a BE20 with MVD = 20 µm

T(°C) / LWC($g\ m^{-3}$)	0	-4	-8	-12	-16	-20	-30
0.0	.000	.000	.000	.000	.000	.000	.000
0.1	.000	.119	.196	.185	.156	.146	.124
0.2	.000	.176	.257	.242	.198	.200	.140
0.3	.000	.187	.267	.242	.195	.216	.176
0.4	.000	.163	.251	.382	.268	.219	.189
0.5	.000	.200	.276	.251	.421	.451	.252
0.75	.000	.191	.291	.273	.232	.226	.242
1.0	.000	.194	.345	.215	.465	.262	.202
1.5	.000	.229	.477	.638	.871	.393	.538
2.0	.000	.185	.390	.305	.530	1.011	.201

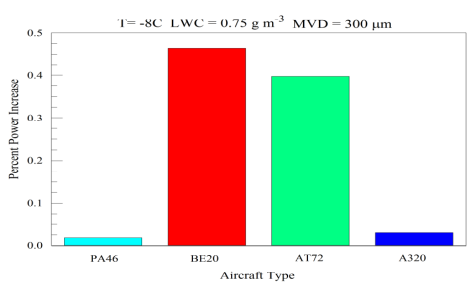


Figure 4. Percent Power Increase values for four different aircraft types for T = -8C, LWC = 0.75 g m^{-3}, and MVD = 300 µm.

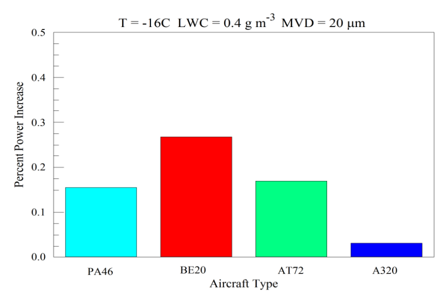


Figure 5. Same as Figure 4 for T = -16C, LWC = 0.4 g m^{-3}, and MVD = 20 µm.

mathematical, statistical, or empirical relationship to describe how ice accumulation affects aircraft performance hence the need to create look-up tables for many airfoils.

We illustrate the variation of PPI values versus atmospheric conditions for a particular aircraft with a sample look-up table (Table 4) we created for the BE20 for MVD = 20 µm. While there is a general increase in PPI with higher LWC and lower temperature, there are some unique conditions that will create higher intensity icing, for example, at T = -12C and LWC = 0.4 g m^{-3}. We estimate that the CFD software computes a PPI with an error about 10%. The PPI of 38.2% in this unique condition is greater by more than 10% of the surrounding points in the table.

Even aircraft with identical airfoil shapes lose performance differently with different aerodynamic characteristics. Illustrated in Figure 6 are the PPI computations for the Beech King Air and the Embraer 120 (E120) which both have a NACA 23012 airfoil shape. The BE20 has a smaller chord (1.60 m) and flies slower (150 kt) than the E120 (1.99 m chord and 200 kt), yet the BE20 shows worse performance loss. The faster one flies, the more cloud liquid water is intercepted, but that effect is apparently more than offset by having the ice accrete over a larger airfoil.

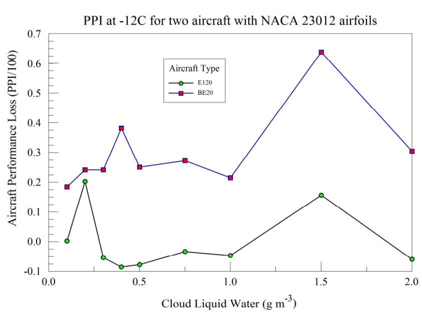


Figure 6. PPI values at -12C for E120 and a BE20 aircraft.

The effect of SLD on aircraft performance has two opinions. Some have observed that SLD tends to uniformly coat an airfoil and does little to reduce performance (Thomas and Marwitz 1995). On the other hand Politovich (1989) and Bernstein et al. (1999) document substantial performance losses in SLD environments. Our analyses suggest that both are correct. Figure 7 shows three different aircraft responses to SLD. The HFB 320 Hansa jet (HF20) shows little PPI change with mean droplet diameter while the Daussalt Falcon 900 jet (F900) actually performs much better in SLD than in a smaller droplet environment. The Cessna 210 Centurion propeller plane (C210) performs much worse in SLD, especially in larger droplet environments.

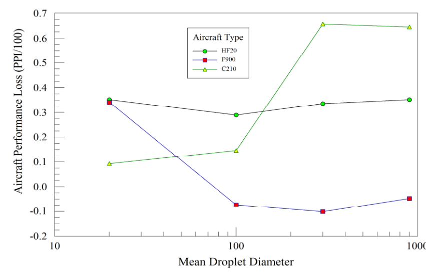


Figure 7. PPI values for HF20, F900, and C210 aircraft at various mean droplet diameters. For all PPI calculations T = -8C and LWC = 0.75 g m^{-3}.

Finally, just because an aircraft performs well in a small time exposure, doesn't mean a pilot flying that airplane shouldn't be aware that icing could become hazardous. Figure 8 shows the PPI after increasingly longer time exposures. Through the initial 17.5 minutes of exposure the Cessna Citationjet /CJ3 (C25B) isn't affected by ice accumulations in these conditions; in fact, the ice accumulation slightly improves its performance. After that time the performance decreases rapidly.

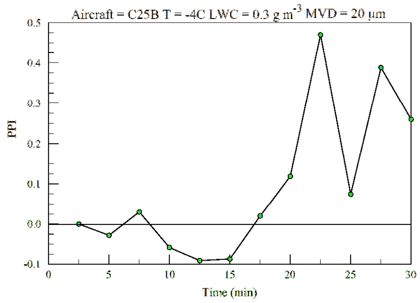


Figure 8. PPI values for a C25B aircraft after various time exposures to the conditions given in the figure.

In all cases we examined, given enough time, light icing will become hazardous, and it is usually within 20 minutes or less. The ATR72 that crashed in 1994 near Roselawn, Indiana, was exposed to icing conditions for 24 minutes. The conditions were not dangerous for a short exposure (PPI ~ 1.5%), but became hazardous (PPI ~ 120%) in 24 minutes (McCann 2004). Because of the dangerous situation that can develop in a short time, we strongly urge the FAA to remove the "(over 1 hour)" phrase from the light icing definition.

4. AIRCRAFT-SPECIFIC FORECASTS

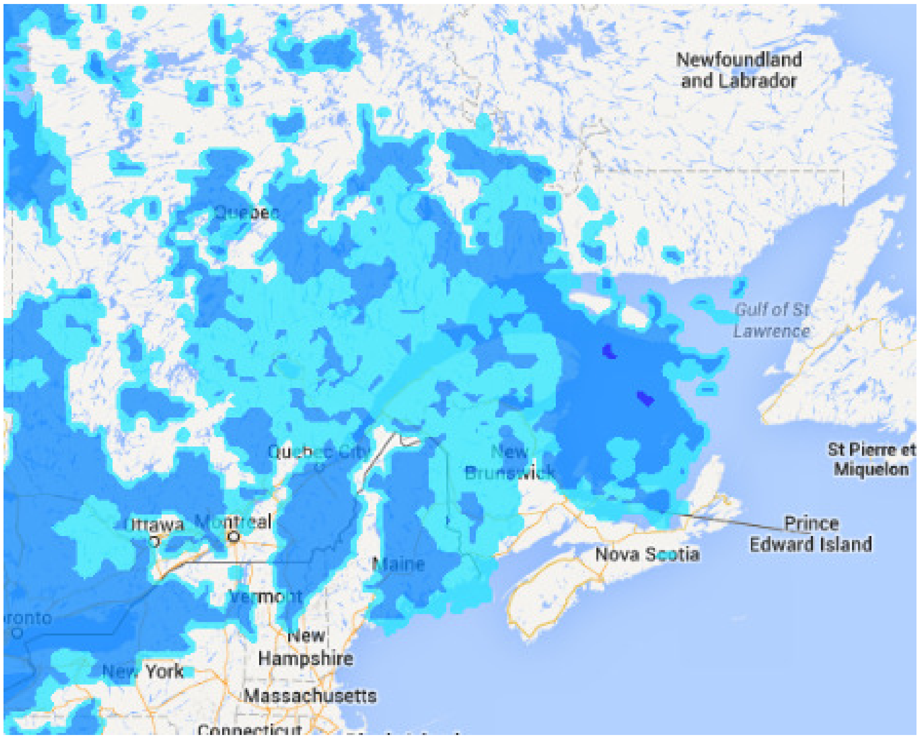
Aircraft-specific icing forecasts can be implemented with any forecast of T, LWC, and MVD. Forecast air temperature is computed by numerical weather forecast models. Some of these models forecast LWCs also, albeit not very well in general. Even fewer forecast MVDs. McCann (2006) introduced the VVICE algorithm which post-processes any numerical model for the LWC and MVD. VVICE parameterizes vertical motions, even convective motions, then uses these in straight-forward cloud physics relationships to create the cloud parameters.

We make two two-dimensional (T, LWC) lookup tables for every aircraft type for which we created a PPI profile. One table is for MVD < 100 µm, and the other is for MVD ≥ 100 µm. The small droplet table is for conditions we analyzed at 20 µm. Sometimes there were considerable differences in the SLD (100 µm, 300 µm, and 900 µm) results that depended on droplet size (Fig. 7). Recognizing that SLD MVD forecasts are probably imprecise, rather than create many tables for the range of SLD, we decided to create just one table using the maximum computed SLD PPI for a given T and LWC.

Many aircraft show a small or even negative PPI in a five minute exposure, for example, Fig. 8. Recognizing that seemingly safe conditions may become hazardous in time, anytime there is LWC > 0 g m^{-3} and T < 0C, we set the PPI = 1% to alert the user to possible dangerous conditions if the user were to loiter too long.

In our product the user specifies an aircraft type, and we interpolate the appropriate PPI profile table at every model grid point, horizontally, vertically, and in time. If the user's aircraft type is not in our database, we have default tables based on aircraft size. Thus, we can create horizontal maps at the user's requested altitude, cross sections along the user's requested flight path, or other useful displays.

Figure 9 shows displays for the same Rapid Refresh model forecast for three different aircraft. While all three displays show the same icing areas, the BE20 map shows extensive areas of higher PPI and even some small patches of very high PPI over eastern New Brunswick. In contrast, the ATR72 map shows smaller areas of higher PPI and even shows low PPI in the same area as the very high values located on the BE20 map. Furthermore, the Airbus 320 (A320) map shows very small areas of higher PPI.


Newfoundland
and Labrador
Quebec
Gulf of St
Lawrence
St Pierre et
Miquelon
Quebec City
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New York
Massachusetts
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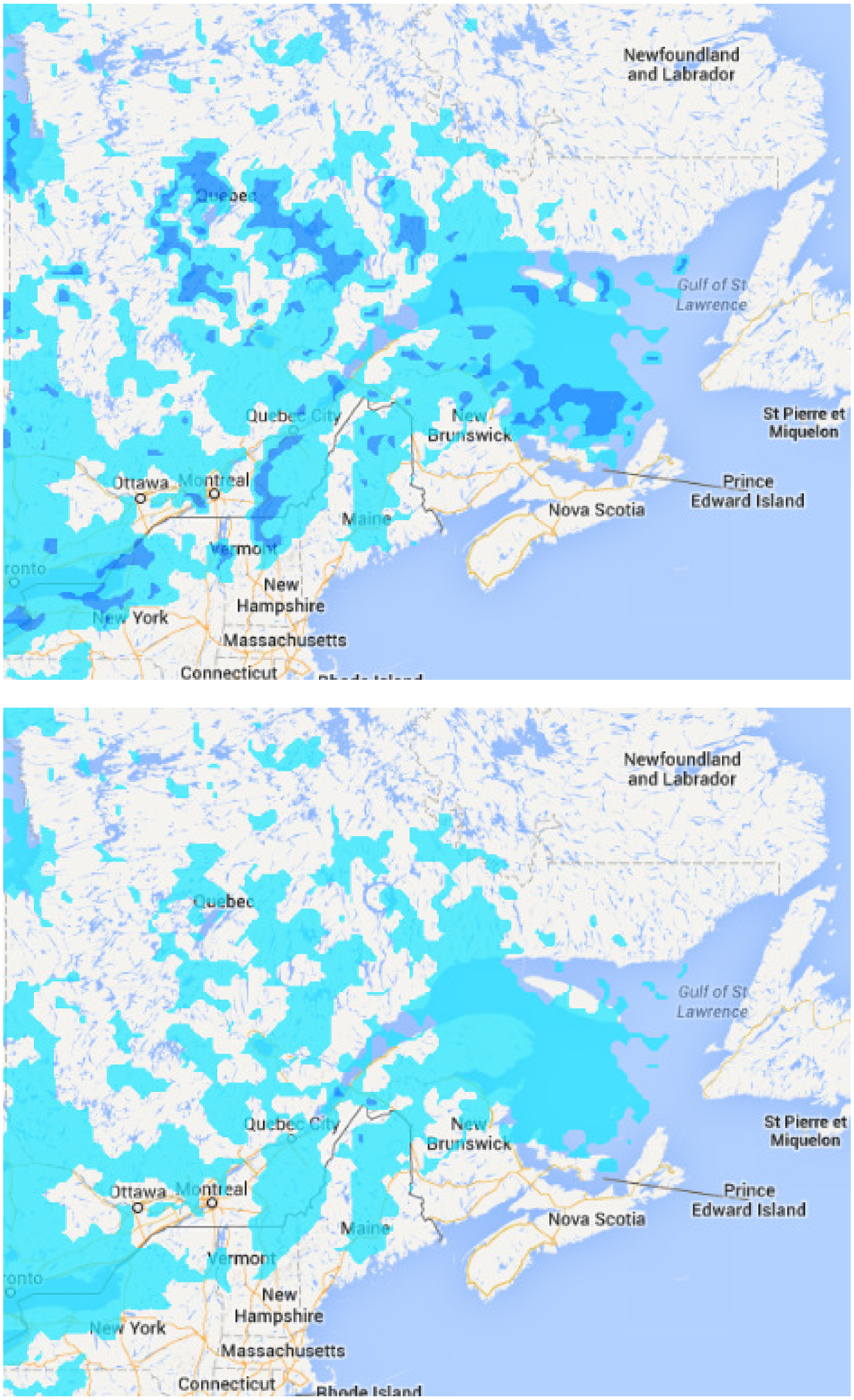

Figure 9. Top) Nine-hour PPI forecast over southeast Canada for a BE20 at 5,000 feet from the 1800 UTC 9 December 2013 Rapid Refresh forecast. Color-fills are light blue (.01), medium blue (.10), and dark blue (.40). Middle) Same as top for an ATR72. Bottom) Same as top for a A320.

5. CONCLUSIONS

Schneider Electric aircraft-specific icing forecasts remove some of the ambiguity in one-size-fits-all icing forecasts. In particular, there may be a unique situation in which a particular aircraft may be more vulnerable to icing than the forecast indicates.

Aircraft-specific icing forecasts will greatly enhance flight planning and route optimization as well as flight safety. Aircraft with a tolerance for icing or with sufficient power reserves will be able to fly into areas where they might not have before. These forecasts will reduce the guesswork for Extended range Twin-engine Operations (ETOPS) which must account for icing because when such aircraft fly on a single engine, it is at a lower altitude increasing the icing risk.

The Percent Power Increase (PPI) icing metric is the cornerstone of our icing forecasts. Without it, we could not express the differences in performance loss among various aircraft. We are unaware of any other metric that directly and objectively measures an aircraft's response to icing and is simple to understand by users and forecasters alike. Since there has been no other proposed metric to date, we recommend that the community adopt PPI as the objective icing metric to use for forecasting.

By assuming one speed and angle of attack for each aircraft analysis, we are assuming that icing is representative of other flight conditions. Our analyses are only of aircraft wings and do not take into account other icing affects such as accretion on the tail, fuselage, and control surfaces. Nevertheless, icing on aircraft wings is the most influential process to lower aircraft performance.

By being aircraft-specific, these forecasts create some intangible goodwill with users. Knowing the icing forecasts are tailored to their aircraft type, users can better embrace the forecasts as meaningful to them. This creates less doubt about how to interpret the forecasts.

ACKNOWLEDGEMENTS

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