P6.3 THE CIP INFLIGHT ICING SEVERITY ALGORITHM

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1. INTRODUCTION

The InFlight Icing Product Development Team (IFIPDT) of the FAA's Aviation Weather Research Program is charged with improving detection and forecasting of inflight icing conditions. The IFIPDT's Current and Forecast Icing Potential (CIP and FIP) have been accepted by the FAA and NWS as operational products. However, only the *potential* for inflight icing conditions is depicted; expected *severity* is not yet included. This limits the products' usability since many airplanes are denied from flying in environments having certain severity categories, and must have access to that information during flight planning.

The IFIPDT has devised an inflight icing severity algorithm which has been undergoing internal testing at NCAR for nearly a year. The rationale for the algorithm is described in this paper, as well as data inputs and ideas for improvement.

2. ICING SEVERITY

Table 1 lists the old and new (proposed implementation date October 2004) icing severity definitions. The reader will note that there is very little meteorological information, even in the new version. Severity, which is what pilots report in flight, is a product of the atmospheric conditions the aircraft encounters and the aircraft's response to those conditions. The response information is also somewhat filtered by the pilot, whose interpretation of the aircraft's response depends on experience, comfort level and confidence. The requirements are that expected icing severity be included with the forecast. Thus, the forecaster has to predict the expected severity the aircraft will encounter, using the available information coupled with experience.

AIRMETs (AIRmen's METeorological Bulletins) include icing severity and type. Forecasters typically peruse current PIREPs and determine what severity is being reported, relate that to current weather phenomena, then extrapolate with weather system movement. To accomplish this, they consult information such as radar and satellite images, soundings, and model outputs to provide their best assessment of expected icing severity, much as CIP does automatically.

3. ATMOSPHERIC INFLUENCES ON ICING SEVERITY

The greatest influences on icing severity are, in order of importance, the liquid water content, the temperature and the drop size (as described by Shin et al. 1991). These factors have been determined through numerical accretion model simulations, wind tunnel tests, and flights in natural icing conditions. The liquid water content describes the total amount of water substance available for accretion on an airplane. The temperature governs the physics of the ice accretion. The drop size controls the collection efficiency and to some degree the texture of the accreted ice. With notable exceptions, the more liquid available, the more ice accretion is possible and the more severe the condition to the aircraft. The Rapid Update Cycle model (RUC, the model used in the CIP) explicitly predicts liquid water content of cloud and precipitation as cloud and rain water mixing ratios. However, these have to date not been rigorously verified using *in situ* data. Our analyses of the liquid water predictions using PIREP data show varying levels of success depending on the radius of influence allowed for RUC comparisons to reported icing. For example, one study reported by Politovich et al. (2002) gave a "hit" for any non-zero 40-km RUC cloud and/or rain water within six grid points (240 km) of the PIREP, and $\pm$1500 ft vertically, showed 59% of the PIREPs having RUC-predicted liquid. More stringent tests have resulted in markedly lower probabilities of detection.

The collection efficiency of drops onto an airfoil is a function of droplet size, airfoil shape, air density and airspeed. Larger drops will collect more readily as they have greater momentum to cross streamlines and impact the surface. In the icing community, the drop size distribution is typically characterized by the median volume diameter (MVD) of the distribution. This is the size at which half the liquid water content is contained in larger (smaller) drops. Finstad et al. (1988) demonstrated that the collection efficiency of

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Table 1: Current and Proposed Icing Severity Definitions

Category	Old Description	New Description
Trace	Ice becomes noticeable. Rate of accumulation is slightly greater than the rate of sublimation.	Not used
Light	The rate of ice accumulation may require occasional use of ice protection systems to remove/prevent accumulation.	The rate of ice accumulation requires occasional cycling of ice protection systems to remove/prevent accumulation. A representative accretion rate for reference purposes is 1/4 inch in 15 min or more on the outer wing. The pilot should consider exiting the condition as soon as possible.
Moderate	The rate of ice accumulation is such that frequent use of ice protection systems is necessary.	The rate of ice accumulation requires frequent cycling of ice protection systems to remove/prevent accumulation. A representative accretion rate for reference purposes is 1/4 inch in 5 to 15 min on the outer wing. The pilot should consider exiting the condition as soon as possible.
Heavy	Not used --- however, in current operational use, pilots often confuse and report “severe” as “heavy”	The rate of ice accumulation requires maximum use of the ice protection systems to remove/prevent accumulation. A representative accretion rate for reference purposes is 1/4 inch in less than 5 min on the outer wing. Continuous pilot vigilance is required and immediate exit from the conditions should be considered.
Severe	The rate of ice accumulation is such that ice protection systems fail to remove the accumulation of ice.	The rate of ice accumulation is such that ice protection systems fail to remove the accumulation of ice and ice accumulates in locations not normally prone to icing, such as areas aft of protected surfaces and areas identified by the manufacturer. Immediate exit from the condition is necessary.

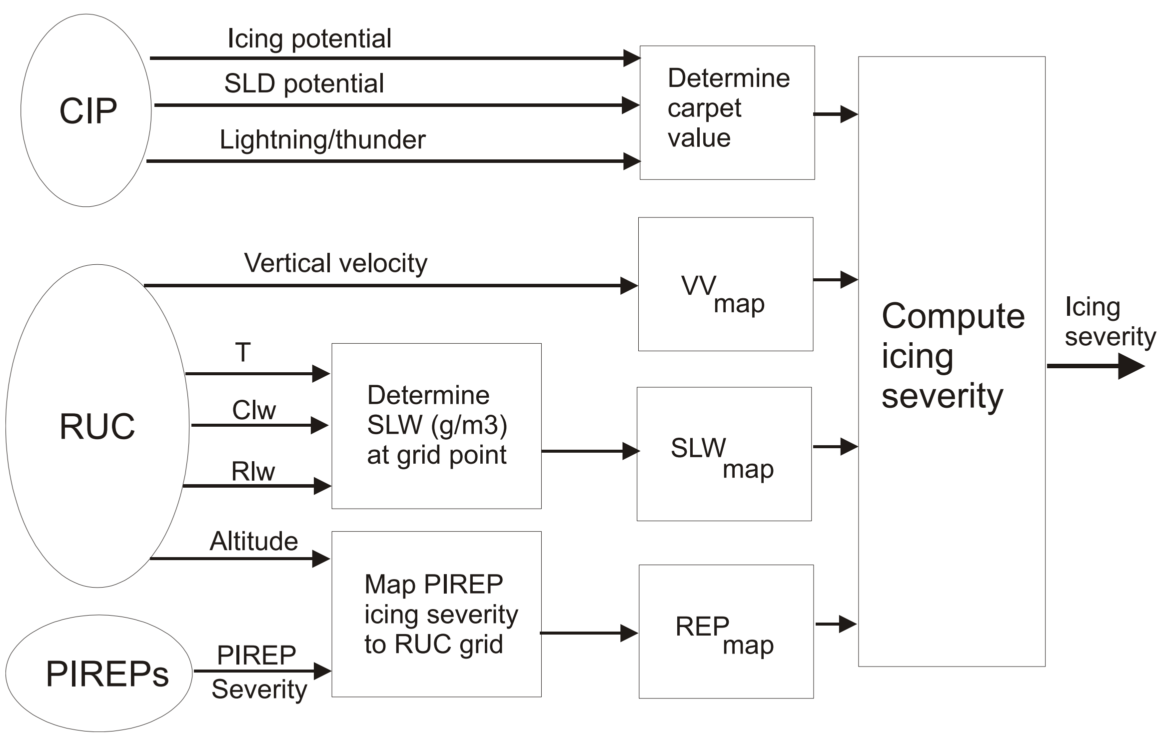

Figure 1: Information flow for the CIP Icing Severity Algorithm. Information from the CIP, RUC and PIREPs is processed from left to right.

typical cloud drop size distributions is well represented by that of the MVD, thus making it very convenient for icing considerations. However, this breaks down when size distributions move far away from Gaussian shapes, such as for drizzle and rain. Summaries of research aircraft measurements by Jeck (1983) and others have demonstrated that in continuous, stratiform clouds, the vast majority (~75% from Jeck's report) of drop MVDs lie between 10 and 20 μm; thus an assumption of 15 μm for MVD is probably adequate for the CIP severity algorithm for non-drizzle and rain cases.

Temperature is predicted by the RUC and the estimates of accuracy tend to lie in the +/-1-2oC range (Wolff, 2004). The information is most critical near 0oC, where there is a transition between sub-freezing and warm liquid which will not accrete on the airframe.

Drop size is not predicted by the RUC, except in a categorical sense (cloud vs. rain, etc.). It is predicted by some research models but is heavily parameterized and not well verified. For most purposes, a nominal value of 15 μm can be assumed given the climatological data described above. In convective clouds (as indicated by the "turning on" of the convective scheme in the model) a larger drop size could be assumed, such as 17 μm. Since this is the third variable in order of significance for icing severity, it is probably not productive to spend a lot of time and effort in calculating it, especially if access to the full drop size distribution is not available.

4. THE CIP ICING SEVERITY ALGORITHM

Armed with this information, the IFIPDT developed an icing algorithm to make best use of current knowledge of the icing process combined with available information. Figure 1 illustrates the information flow. Information is mapped to the underlying 20-km RUC grid. Membership functions are applied to create interest fields, each describing the significance of the information to icing severity. The fields are combined and presented as a final icing severity product.

4.1 Underlying Fuzzy Map --- "Carpet" Value

The CIP Icing Severity Algorithm begins with a floor value assumed from information coming out of the CIP icing potential product. It works on an 8-level scale, with 1=trace icing, 2=trace-light, etc. through 8=severe icing (as in Table 2). Since this is a fuzzy logic algorithm, this fuzzy floor value has been named our "carpet" value and works in this manner:

- If the CIP icing potential >0.05, assume a light icing condition (carpet = 3/8 or 0.375).

- If the CIP SLD potential >0.05, assume a moderate icing condition (carpet = 5/8 or 0.625). If there is deep convection – lightning within 25 km -- a SLD condition is assumed.

SLD areas are included in this severity estimation even though the drop size distributions may violate the 15-μm MVD assumption described above. The SLD areas are still flagged separately in the CIP icing potential output. Product users should still consult the CIP SLD field to check for those conditions.

Membership functions based on liquid water content, vertical velocity and PIREPs are applied to the SLW, vertical velocity and recent PIREPs, then used to adjust the carpet value up or down.

Table 2: PIREP Scaling Used in the CIP Icing Severity Algorithm

8-point scale	INTEREST (PIREP)	Meaning
-9	-9	No information
0	0	No icing (null)
1	0.125	Trace
2	0.25	Trace-light
3	0.375	Light
4	0.5	Light-moderate
5	0.625	Moderate
6	0.75	Moderate-severe
7	0.875	Heavy
8	1	Severe

4.2 Supercooled Liquid Water

The algorithm takes the model subfreezing cloud and rain water mixing ratios and converts them from g g^{-1} to g m^{-3} as in Table 3 and Fig. 2. The membership function is adapted from thresholds calculated by Politovich (2003) and describe an ice accretion rate-based severity index for a variety of aircraft types. There is no penalty if SLW = 0, since we have found a significant fraction (at least 40%) of icing PIREPs occur where the RUC has predicted no liquid. Thus, where there is no liquid predicted by the RUC we assume there is no information, not a true lack of liquid water.

Table 3: INTEREST(SLW)

SLW (g m^{-3})	SEVFUN(SLW)
<0.008	0
0.008-0.4	2.5* SLW
>0.4	1

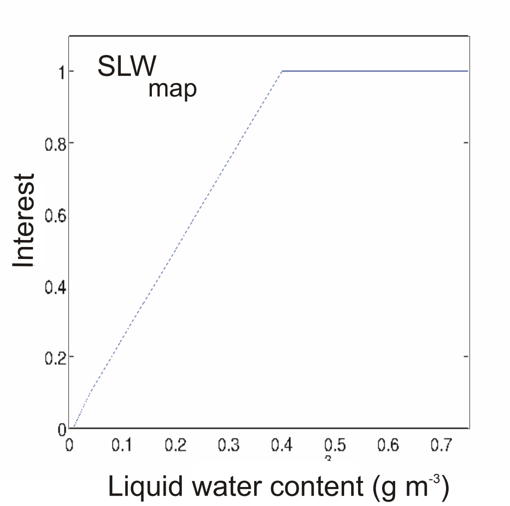

Figure 2: INTEREST(SLW) -- Supercooled liquid water content membership function for the CIP icing severity algorithm.

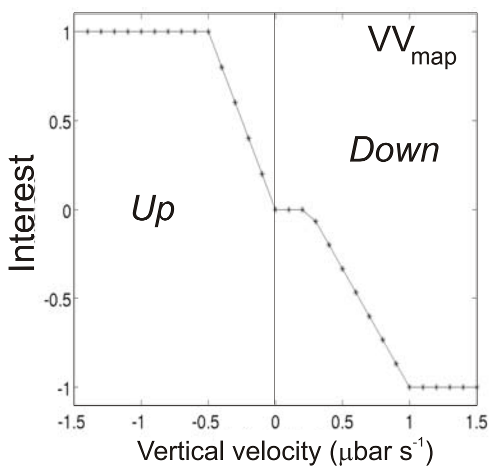

Figure 3: INTEREST(VV) – Vertical velocity membership function for the CIP icing severity algorithm.

4.3 PIREPs

All icing PIREPs for the hour previous to a CIP run are mapped to the RUC grid. Each PIREP is given an "influence disc" sized $\pm$1000 ft vertically with a 100-km radius from the report. Any RUC grid point within that disc is tagged with the PIREP severity given as described above (8-level scale as in Table 2), along with negative reports. The assigned value decreases with distance from the PIREP within that influence disc. For multiple PIREPS in a grid box, the highest severity is assigned. The number of PIREPs in any RUC grid box is not considered since there are naturally more reports near high traffic areas, thus higher numbers of reports may be related more to air traffic activity than to the atmospheric condition.

4.4 Vertical Velocity

We assume that rising air has greater potential for producing liquid water, which is reflected in Fig. 3. The RUC microphysics may not correctly partition condensate into liquid or ice, thus, we give a boost to the potential for more liquid, and thus more icing severity, for rising air. This removes the exclusive dependence on the microphysics package. Note that it also does not account for liquid depletion due to ice processes such as preferred deposition or riming; this boosting factor is meant to reflect the potential for production of liquid condensate by rising and cooling air.

4.5 Combining Fields

Each of the three augmenters is given an equal weight of one-third and all are combined numerically as:

ICESEV = f(CARPET, SEVFUN(SLW),
SEVFUN(PIREP), SEVFUN(VV))

SEVFUN(SLW) = (1-CARPET)*INTEREST(SLW)
SEVFUN(PIREP) = (INTEREST(PIREP) – CARPET)
SEVFUN(VV) = (1-CARPET) * INTEREST(VV)
(for rising air motions)
SEVFUN(VV) = CARPET * VVMAP
(for sinking air motions)

ICESEV = CARPET
+ 1/3(SEVFUN(SLW)
+ 1/3(SEVFUN(PIREP)
+ 1/3(SEVFUN(VV))

The final ICESEV value is scaled 0-1 according to Table 2. Some adjustment may be needed in the final display as a result of verification using PIREPs and research aircraft data. Verification is discussed by Fowler et al. (2004), elsewhere in this conference proceeding.

4.6 An Illustrative Example

Plots of ICEPOT (CIP Icing potential), RUC liquid water content, PIREP interest mapped to the CIP grid, RUC vertical velocity and icing severity (Fig. 4) illustrate the CIP severity algorithm process.

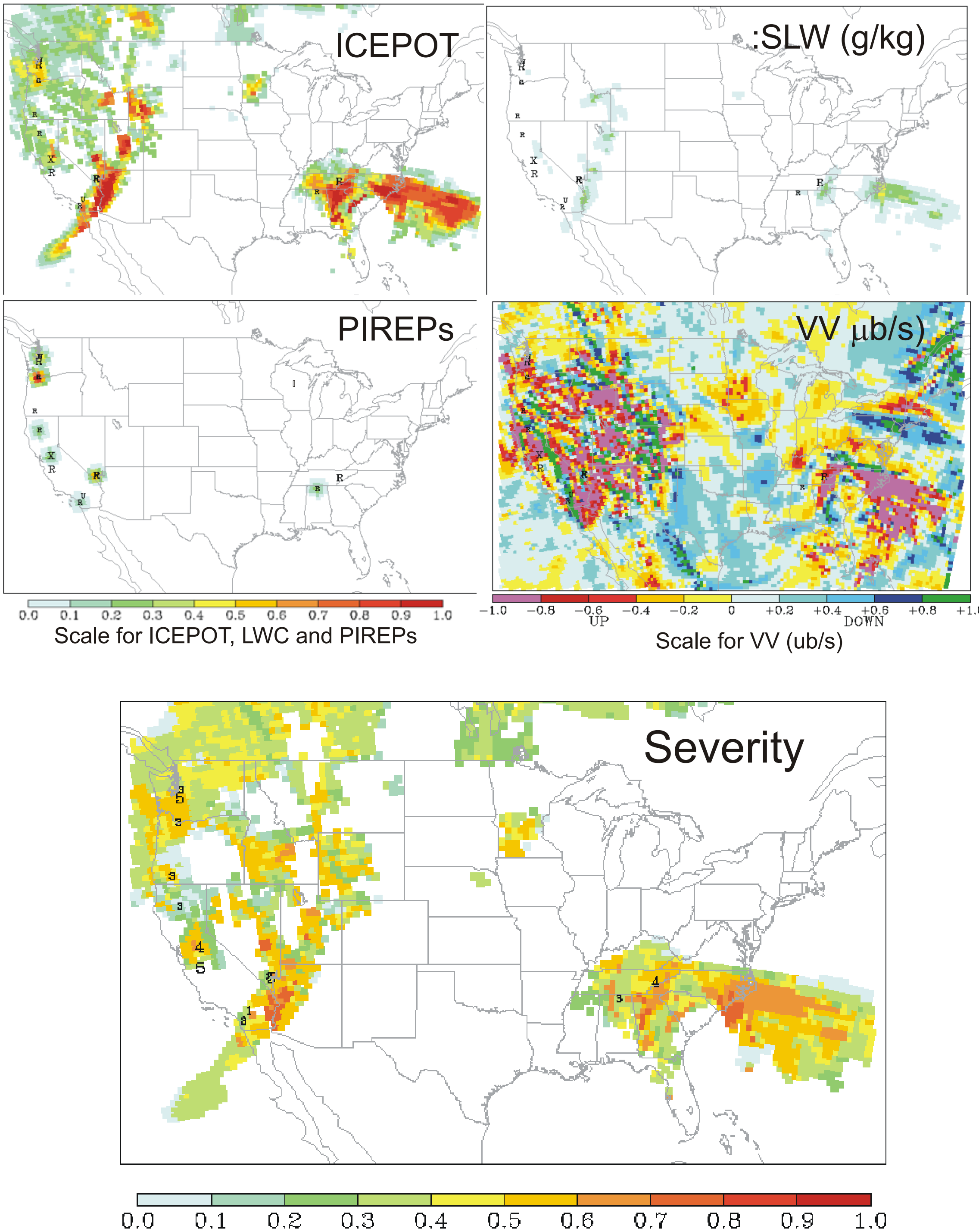

Figure 4: CIP inputs and outputs for 1900 UTC, 26 February 2004 at 12,000 ft MSL. Numbers on the plots are PIREPs of icing coded as in the scale shown. ICEPOT *is the CIP-produced icing potential; SLW, PIREPs, and VV are the interest fields for those parameters, and Severity is the final severity algorithm output.*

The main weather features are in the west and southeast U.S. In the west, a vigorous cold front and associated cloudiness are moving eastward. This creates high icing potential near the front with decreasing potential behind. RUC places liquid water near the front. PIREPs appear near the Pacific coast where there lingering cloudiness in widespread upward-moving air. The severity values were mostly in the 0.2 – 0.7 range, which without further calibration represents light to moderate icing.

The weather in the southeastern U.S. features a low pressure center with a warm front moving across the Carolinas, and a cold front extending southward into Florida. This is reflected in the icing potential, liquid water content and vertical velocity fields similar to those associated with the weather in the western U.S. PIREPs appear near the center of the low. Regions of higher severity are more widespread than in the west, particularly ahead of the large-scale lifting around the warm front. Severities there are consistently moderate, surrounded by light-moderate and lower values, with some embedded moderate-heavy icing.

5. ALTERNATIVE SOLUTIONS

We have considered alternative solutions listed in Table 4. The reasons for rejecting these approaches is also listed; we believe that given the information now operationally available to the CIP, the severity algorithm described in this paper represents sound physical principles.

Table 4: Alternative Methods for CIP Icing Severity and Reasons for Rejection

Alternative	Reason for Rejection
Assume all icing depicted by CIP is moderate or greater for some minimum threshold. In terms of POD and volume covered, the CIP likelihood value of 0.15 roughly corresponds to an AIRMET.	We can do better with the information we have.
Just use the RUC LWC as a severity indicator.	RUC microphysics parameterizations are still not adequate.
Match CIP/FIP icing areas to the nearest AIRMET and assign severity	Many regions exist with no AIRMETs, plus, this is not in line with future concepts of a fully automated system.
Run an internal cloud model that raises parcels from the CIP/FIP-designated base and grows drops adiabatically	Prohibitively expensive in terms of time; current simplified methods are inadequate.

6. UPGRADES

While we have implemented an initial severity algorithm, we are considering these upgrades:

Adjust the carpet value to vary with CIP icing potential values:. While the CIP icing potential is not severity, much of the information that goes into determining the potential for inflight icing in the CIP algorithm is the same that a forecaster would use for determining severity. This information should be taken advantage of more so than it is at present.

Enhance use of the RUC microphysics fields: Cloud and rainwater mixing ratios are used in the current version; graupel, ice and snow could be used in situations where the condensate appears to be mis-typed. Past studies have shown that nearly all icing PIREPs occur in areas where the RUC predicted *some* form of condensate. More research into values associated with icing should be done first.

Better treatment of SLD areas: Results of performance analyses from flights in natural icing conditions suggests that a combination of the presence of SLD and certain thresholds of SLW content are those posing the greatest hazards (Politovich, 1989; Miller et al., 1998). When RUC microphysics are improved, a different severity index incorporating predicted SLW content could be combined with the SLD potential to predict severity in those areas separately. This would have the advantage of providing additional guidance if new icing certification envelopes including SLD are adopted by the FAA.

Incorporate additional parameters: Cloud base temperature and cloud depth are two candidates; these are intermediate products created within CIP. Intermittency of clouds and cloud type could be added; incorporation of these algorithms which are currently used by the convective weather PDT is being considered.

7. SUMMARY

The CIP icing severity algorithm was designed to take advantage of current knowledge of the factors controlling severity of icing along with available information on the atmospheric condition. This product is a response to user needs and should be helpful to aviation decision makers from meteorologists to pilots.

The algorithm was developed at NCAR in 2002 and was implemented locally, where various refinements have been made based on daily inspection and comparison with PIREPs. It is now ready for experimental implementation as part of the Aviation Weather Technology Transfer process (see Knapp et al., 2002). Verification has been conducted (Fowler et al., 2004) and will continue as the algorithm is upgraded.

The CIP icing potential output is used to assign a basis, or carpet, value which is adjusted by SLW (combination of supercooled cloud and rain mixing ratio) and vertical velocity forecast by the RUC, as well as the severity of nearby pilot reports of icing. The final output is a three-dimensional depiction of expected icing severity. A forecast product (for FIP) is also being developed which will not have the advantage of the pilot report information. Alternative solutions have been considered and upgrades will be made as improved information on parameters related to inflight icing severity is available.

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