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THE NEW CIP ICING SEVERITY PRODUCT

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1. INTRODUCTION

Current Icing Potential (CIP) became operational in 2002, producing hourly, three-dimensional, gridded icing products. These products combine cloud physics principles with forecaster knowledge and fuzzy logic membership functions to assess the likelihood of the presence of supercooled liquid water (SLW; icing potential) and supercooled large drops (SLD potential) using satellite, radar, pilot, surface and lightning observations in combination with numerical model output (Bernstein et al. 2005). While these products provide useful information on the location of icing conditions and lack thereof, they are not calibrated into actual icing probability and do not provide a direct assessment of icing severity. This has limited their practical use for decision making, especially by pilots.

In an effort to remedy these limitations, CIP developers recently created an experimental icing severity product (Politovich et al. 2004). The field was initiated with a baseline assessment of severity based on icing and SLD potential, then adjusted upward or downward based on Rapid Update Cycle model (RUC; Benjamin et al. 2004) forecasts of vertical velocity and explicit SLW, and the nearest reported icing severity from pilot reports (PIREPs) within 125km. This initial product showed skill, but experience from multiple field programs indicated that additional skill could be gleaned by furthering the use of several fields already ingested into CIP, including many not directly used in the experimental version of CIP severity. In this paper, a planned upgrade to the CIP severity algorithm will be described, including the concepts and development methodology used, as well as the output that it produces.

2. ICING SEVERITY – A COMPLEX ISSUE

As noted by Sand and Biter (1997), reported icing severity is the result of a complex interaction between the meteorology (temperature, liquid water content and drop size spectrum) and both the aircraft and pilots that encounter those conditions. Aircraft response depends upon the aircraft type (from large transport to small trainer), ice protection system (boots, heaters, etc. or a lack of protection), phase of flight (climb, cruise, hold, descent), and flight history (e.g. cold soak). All of those aspects must be combined with pilot perception, which is a function of overall and type experience, past icing experience and the situation at hand. The same icing environment can result in very different reported icing severity, depending on the aircraft and pilot factors. A bleed-air protected large jet climbing quickly through a widespread stratocumulus layer with SLW of 0.25 gm^{-3} and temperature of -8°C at its top may only notice a short burst of light icing, while that same aircraft and pilot holding within the top of this same layer may consider the icing to be light-to-moderate. A smaller, booted aircraft in a similar hold may consider the icing to be moderate. While the differences between these flight situations may be discernable, as developers we must first and foremost focus on the meteorology of icing, which is complex enough!

The primary contributors to icing severity are liquid water content (LWC), temperature (T) and drop size, with LWC and T being the dominant factors (Hansman 1989). Temperature is handled quite well by numerical models, but LWC and drop size are a different matter. Recent studies have shown that while model microphysics packages have improved, they continue to be inherently dependent on the ability of the model to correctly predict the dynamics and thermodynamics, and in particular, the presence of saturation at each location. Small errors in system timing, vertical velocity, stability and moisture initiation can mean all the difference in the production of a model cloud, only after which can the microphysics package kick in. Even if those portions of the forecast are perfect and water is correctly produced at a given level, the amount of water at that level depends upon the levels above and below it that might contribute to or decimate the liquid (Thompson et al. 2006). Furthermore, even if the prediction of LWC is perfect, the prediction of drop size is highly dependent on airmass cleanliness. The cloud- to rain-water conversion rate is typically held constant, resulting in an inappropriate conversion rate for many situations. It is these types of problems that handcuff

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the RUC microphysics package to the point where it only correctly identifies the presence of SLW for ~25% of all positive icing PIREPs. Thus, at this point, the model can not be solely depended upon to diagnose or forecast the presence or amount of SLW or drop size.

Fortunately, after spending more than ten years analyzing and forecasting icing for flight programs, CIP developers have identified many features in observational and model-based fields that provide information on cloud phase, LWC and drop size. Only anecdotal evidence for their effectiveness had been gathered to date, so these fields were subjected to rigorous testing during the development of the new version of CIP Severity.

3. CONCEPT AND CANDIDATE FIELDS

As always, CIP developers strive to focus on blending the principles of cloud physics with forecaster experience and an understanding of the limitations of the data sets that are operationally available. Each field has its strengths and weaknesses for estimating SLW production and depletion, many of which depend upon the context in which they are used. Because of this, icing scenarios were identified and the meaning of a given parameter was assessed situationally.

Icing scenarios chosen for severity analysis were similar to those already used in CIP. The scenarios were: single layer non-precipitating clouds, multi-layer clouds (each layer treated uniquely), warm rain clouds (liquid precipitation and CTT [cloud top temperature] > -12^{o}C), cold rain (same, but with CTT < -12^{o}C), all-snow (snow and only snow reported at the surface), classical freezing rain – below the warm nose (beneath the melting zone in a classical freezing rain temperature structure with freezing or liquid precipitation reported at the surface), classical freezing rain – above the warm nose (above the melting zone), and deep convection (lightning within 25km in the previous 15 minutes).

Each member of the development team was asked to independently create a list of the fields that they thought were useful for the diagnosis of icing severity, and tag it with a situationally-based weight between 1 (slightly useful) and 5 (very useful). The lists were combined, weights were discussed and a consensus was reached. Initial membership functions were developed for fields where appropriate.

To facilitate internal algorithm development and getting CIP Severity to operational status by winter 2006-07 (pending approval by the Aviation Weather Technology Transfer [AWTT] Board), the team decided that fields used in this version of the algorithm would be limited to those that could be derived from datasets already ingested into the operational CIP running at NOAA's Aviation Weather Center. Other fields were tested for their potential application in future versions of the code, with nearly 200 tested in all.

Using every third day from a 3-month database from 6 January – 5 April 2005, more than 5400 icing PIREPs and 377 20-km averages of research aircraft data were mapped to the gridded observations and model output. The remaining two-thirds of the days were set aside for the planned verification, as part of the AWTT process. Values from the candidate fields and their associated interest maps valid at each 3-D aircraft location were matched to the icing severity reported in each PIREP or the 20-km average of SLWC (supercooled LWC) from research aircraft. Scatter plots and box diagrams were examined to assess the statistical relationship between the aircraft observations and the candidate fields. This was done both in an overall sense and for the individual icing scenarios. Following this, some interest maps were adjusted, new derivative fields were developed and weights were adjusted. Some fields were eliminated.

4. INITIAL SEVERITY – SLW PRODUCTION

After the winnowing process was completed, candidate combinations of fields were tested for each icing scenario. The approach used to calculate icing severity is different from the multiplicative approach used to calculate icing potential in CIP (e.g. ICPOT = $T_{map}*CTT_{map}*RH_{map}$). Since each field is intended to provide its own indication of the SLWC, the initial severity (SEV_{init}) estimate is calculated using a weighted summation approach that is tempered by the confidence in each field:

$$SEV_{init} = (c_1w_1a_1 + c_2w_2a_2 + ...) / (c_1w_1 + c_2w_2 + ...)$$

where a is the field value, w is the weight and c is the confidence in the field. The weight is used to show the amount of meaning or value that a given field has in the determination of the SLWC that could be produced at a given location. Confidence information is included because the quality of the information contained within a given field may not be static. For example, confidence in visible albedo from satellite changes dramatically during the day. It may be high at midday when clouds are well illuminated, but erodes as the solar terminator approaches and goes to zero at night. Likewise, it may decrease toward the north, especially in winter. Thus, the influence of the visible albedo field is tempered by a confidence parameter that is based upon solar zenith angle.

This is one example of how the algorithm makes better use of fields already available to CIP. There are far too many to describe in this paper, but some examples are described below.

4.1 More on satellite data

In the original CIP, satellite data were primarily used to identify the presence of clouds and to estimate cloud top temperature and height. In daily forecasting, developers have used visible albedo to provide a feel for cloud top LWC when they were confident that the cloud tops were, indeed, water dominated. Lee et al. (1997), Thompson et al. (1997) and others have shown that the difference between channel-2 and channel-4 provide insight into cloud top phase, with large values tending to indicate water and small values tending to indicate ice crystals during the day. A membership function applied to this difference field is used in combination with solar zenith angle to determine the confidence in the use of visible albedo for CIP cloud layers visible from satellite (as in Fig. 1). When visible albedo and confidence values are high, then relatively large amounts of SLW are expected at cloud top. Similar information to this is used in the calculation of liquid water path by Minnis et al. (2004).

4.2 PIREPs

Pilot reports are also applied more judiciously than in the initial severity algorithm. The original CIP only used positive reports to boost the confidence that icing was present, and did not make use of negative reports because of their inherent biases. In practice, forecasters amass information from both positive and negative icing reports, considering recent, nearby reports to be more meaningful to the icing severity at a given location than reports that are older and father away. Eventually, reports are too old and/or far away to be of value. It is in this fashion that CIP Severity uses PIREPs. All PIREPs made within the last two hours before the valid time (e.g. 1600-1759 for an 1800 UTC run) are mapped to the CIP grid. Their age (minutes from valid time), and their horizontal and vertical distance from each grid point are calculated. For each grid point, all PIREPs that were within 300km horizontally and ~1.2km (4000 ft) vertically are considered. The value of a given PIREP is on a scale of 0 to 1, dropping off with age after 15 minutes, horizontal distance after 30km and vertical distance.

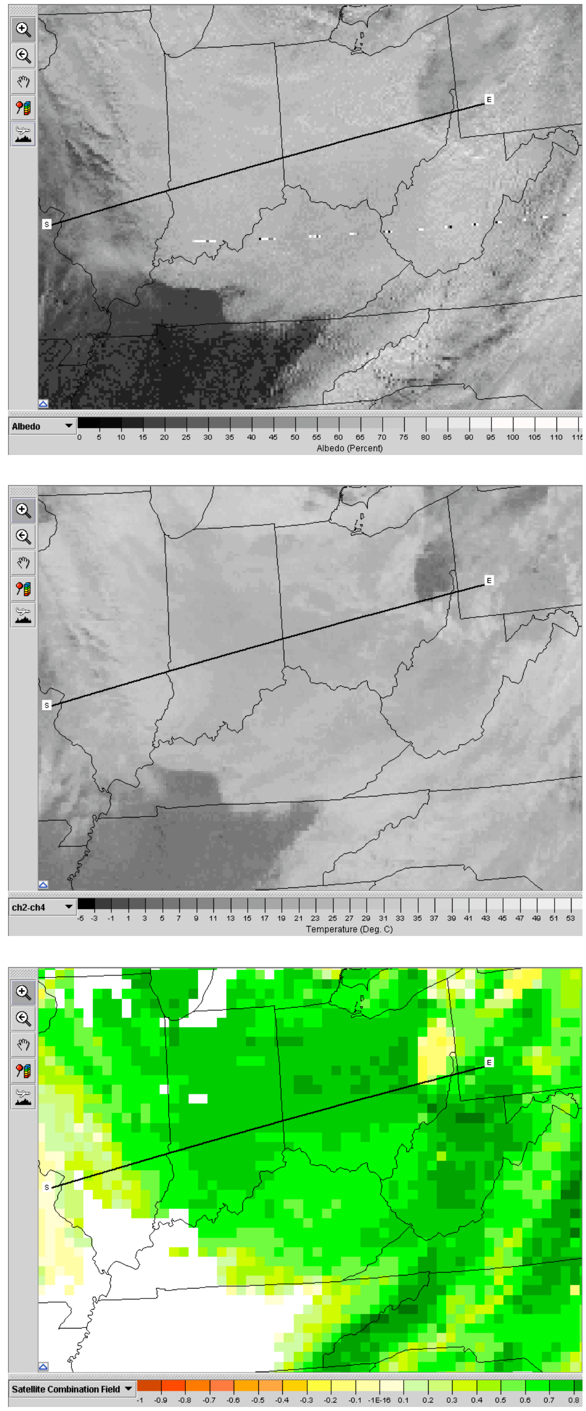

Fig. 1. Satellite fields for 1800 UTC on 19 Jan. 2005. a) Visible albedo (%), b) channel 2 minus 4 (^oC) and c) "satellite combination", showing interest for icing severity (yellow is low, dark green is high). Note that the field is only defined where icing potential is positive. Icing potential=0.0 over southern Illinois, so satellite combination was undefined there. The cross-section "s" to "e" is used in later figures.

A consensus severity is calculated by summing up the product of the severity (s; range 0 [null] to 8 [severe]) of the PIREP and its value (v), then dividing by the sum of all of the values:

$$REP_{sev} = (v_1 s_1 + v_2 s_2 + ...) / (v_1 + v_2 + ...).$$

This consensus severity proves to be an excellent predictor of severity reported close by in the near future, while the sum of the values (the denominator) provides a sense of the confidence in the PIREP information mapped to each location. The sum of the values is a combination of the number of PIREPs available to make the severity estimate, balanced by both their closeness and recency.

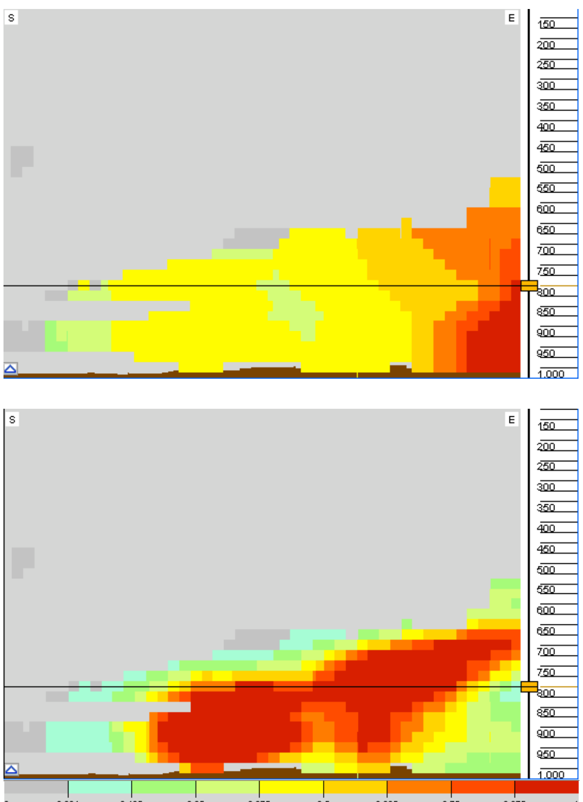

Fig. 2. Icing PIREP mapping results along cross section from "s" to "e" in Fig. 1 at 1900 UTC on 19 January 2005 – one hour following the PIREPs shown in that figure. a) Blended icing severity and b) PIREP weight. The scale in (a) is from 0.0 (null icing) to 1.0 (severe icing), with light and moderate icing represented by values of 0.375 (3/8) and 0.625 (5/8), respectively. The scale in (b) is from 0.0 (no weight) to 1.0 (full weight), given the number, proximity and recency of the PIREPs to each location. Y-axis values indicate pressure (mb).

Figure 2 shows an example vertical cross section of this field along the line from "s" to "e" in Fig. 1. The PIREPs shown in Fig. 1 are for the period 1800 to 1859 UTC, while those PIREPs (and those from 1700 to 1759 UTC) were used to make the analysis valid at 1900 UTC, which is shown in Fig. 2. Recently reported PIREPs near this vertical cross section indicated increasing severity (Fig. 2a) toward the right (east-northeast), going from null (grey) through light and light-to-moderate (yellow) to severe (dark red). However, the confidence in this blended severity analysis is strongest in the red areas in Fig. 2b, where more PIREP information was available. Thus, that information plays a greater role in the assessment of icing severity along this cross section.

4.3 Δq

In some cases, LWC can be estimated by employing the adiabatic assumption (as in Tafferner et al 2003). Of course, the ideal situation is a non-precipitating cloud with a moist adiabatic lapse rate. In this case, one can simply subtract the mixing ratio at the level in question from the mixing ratio at cloud base, then use density to convert Δq to an LWC.

The adiabatic assumption breaks down and this method of LWC calculation will typically result in an incorrect estimate if a) precipitation is falling from the cloud or b) the lapse rate differs from moist adiabatic. For these reasons, Δq is only used as in ingredient for clouds with nearly moist adiabatic lapse rates that are non-precipitating or that are producing very light precipitation via the collision-coalescence process. For the latter case, the LWC estimates are damped somewhat, and for both cases they are damped based on the increase in the stability beyond moist adiabatic beneath the level of interest.

5. DAMPING FACTORS AND THE FINAL ICING SEVERITY

The initial icing severity calculation is essentially an estimate of the SLWC that would be produced at a given location. For the most part, it does not account for depletion by ice crystals that could partially or completely glaciate a given environment. Bernstein et al. (2005) showed that information on temperature, cloud top temperature and precipitation falling from a cloud, including its type, can provide valuable insight regarding SLW depletion by ice crystals. In short, as the temperature at a given location decreases beyond about -12^{o}C, the chances for ice crystals to be produced there increases markedly. The ice crystals produced can fall through the clouds below, also depleting SLW.

With this in mind, the temperature and cloud top temperature of a given layer are used to decrease the SLWC (and thus, severity) estimate at a given level by as much as 50% and 20%, respectively. The effect of CTT includes a damping factor because confidence that a given cloud layer is vertically continuous decreases with increasing distance below cloud top. If temperature at both a given level and cloud top are relatively warm, then the severity is unaffected, since SLW is expected to dominate.

In general, radar echoes near the surface indicate that precipitation-sized particles are being produced by and/or falling through the lowest cloud layer. This represents a sink of SLW, either through riming or through fallout via conversion to rain or drizzle. Because of this, the application of radar reflectivity as a depletion factor is somewhat complex, since its meaning depends upon the particle type being observed by the radar. A reflectivity of 25dBZ means something very different for cold rain than it does for warm rain or snow. Thus, unique membership functions were developed for several precipitation type categories and their application is dependent upon the icing scenario (see Fig. 3). At most, the radar reflectivity is used to decrease the original estimate of icing severity by as much as 15%, and the amount of decrease is dependent on precipitation type. The effect includes a damping factor because confidence that the observed precipitation fell through a given level within the lowest cloud layer decreases with increasing distance above cloud base.

The damping equations used are as follows:

$$T_{adj} = 0.5 * SEV_{init} * T_{map}$$
$$CTT_{adj} = 0.2 * SEV_{init} * CTT_{map} * C_{z\text{-}CTT}$$
$$RAD_{adj} = 0.15 * SEV_{init} * RAD_{map} * C_{z\text{-}RAD}$$

$$SEV_{final} = SEV_{init} - T_{adj} - CTT_{adj} - RAD_{adj}$$

where $C_{z\text{-}CTT}$ and $C_{z\text{-}RAD}$ are the Δz based confidence factors for cloud top temperature and radar.

In the most extreme case, when T and CTT are low, radar reflectivity is high, and the altitude in question is close to both cloud top and cloud base, then the initial severity estimate can be decreased by as much as 85%. In this unusual circumstance, an initial estimate of moderate icing could be changed to a final estimate of trace. Most often, initial estimates remain unchanged or only change by one category (as in the upper-right portion of Fig. 4; decrease from ~0.6 to ~0.3 represents a categorical change from moderate to light). The definition of the severity categories will be described in the next section.

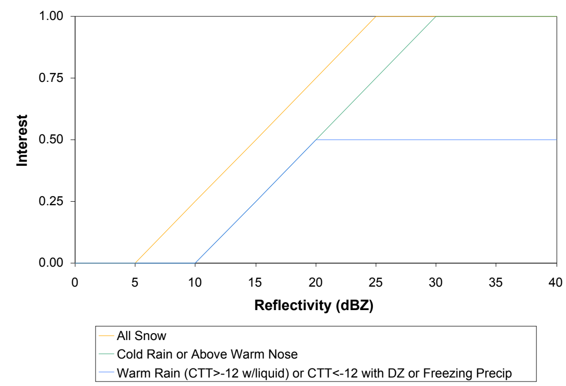

Fig. 3. Precipitation type-based radar reflectivity interest maps used as part of the damping factor.

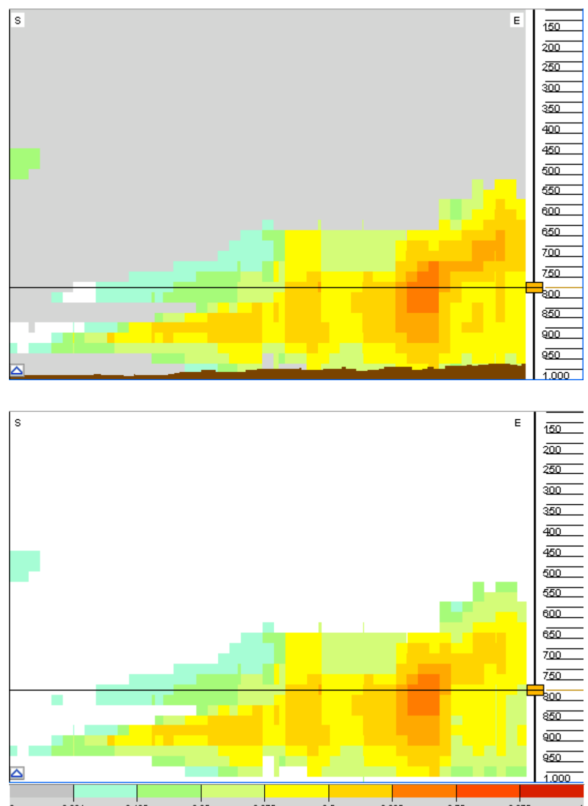

Fig. 4. Initial and final severity products along the cross section from "s" to "e" shown in Figs. 1, 4.

6. SEVERITY CATEGORIES

While icing severity is calculated on a 0.0 to 1.0 scale, the final icing severity field is output into five categories, each representing a range of values (see Table 1).

Severity	Range	% of icing	% of SLWC**
Null	0.0	89.5*	20.1
Trace	0.01-0.2	40.8	34.9 (0.05-0.1)
Light	0.2-0.45	38.1	36.1 (0.1-0.2)
Moderate	0.45-0.75	14.3	17.8 (0.2-0.3)
Heavy	0.75-1.0	1.2	11.2 (>0.3)

*Table 1. Icing severity categories and corresponding numerical range, percentage of all icing diagnosed by CIP that fell into that range (*amount of grid with no icing, remaining values are the percentage of all positive icing that fell into each category), percentage of research aircraft 20-km average SLWC (**Null value is the percentage of all flight time where 0 gm^{-3} was observed, while remaining values indicate the percentage of all time that SLWC > 0.05 gm^{-3} was observed. Values of 0.01-0.05 gm^{-3} are ignored because of noise in CSIRO probe data.*

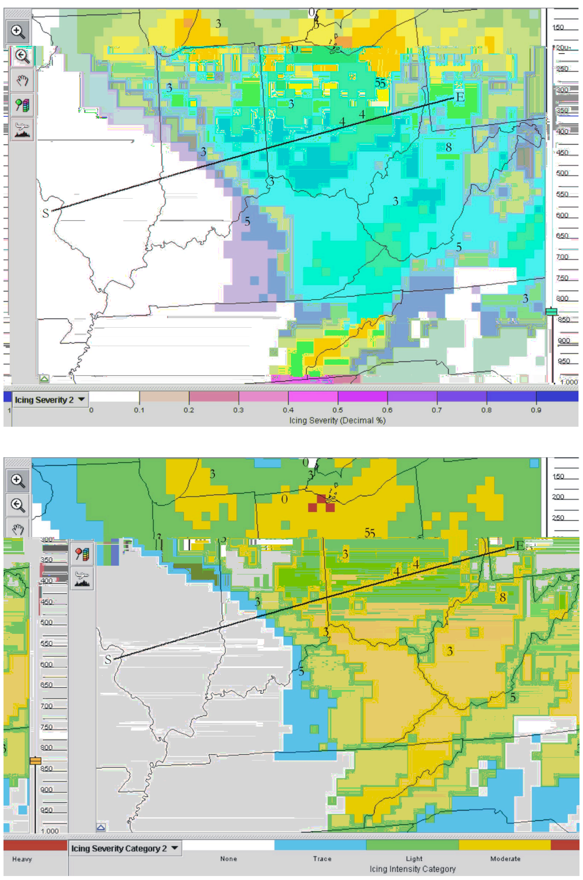

Fig. 4. Numerical (0.0-1.0) and categorical (null, trace, light, moderate, heavy) representations of icing severity at 825mb (~6000ft MSL) at 1800 UTC on 19 January 2005. PIREPs within 1000ft vertically are shown. Severities are as follows: 0=null, 3=light, 4=lgt-to-mod, 5=moderate, 8=severe.

Examination of CIP output from the 3-month test period shows that the severity field indicated "null" icing over 89.5% of the entire CIP grid, three-dimensionally. The domain includes southern Canada, the continental U.S. northern Mexico and adjoining nearby waters, and covers altitudes from the surface to 30,000 ft MSL. Of the remaining 10.5% of the grid where at least some icing was indicated, the vast majority has severities of trace or light (78.9% combined), while moderate and heavy icing were indicated within only 14.3% and 1.2% of the icing areas (~1.5% and ~0.1% of the entire grid).

This compares reasonably well to 20-km averages of research aircraft SLWC observations made during several flight programs that occurred between 2003 and 2005. They show that most icing observed had trace or light amounts of SLW. While 29% of the 20-km SLW averages fell into the moderate or heavy range, be aware that this dataset is *strongly* biased upward because the purpose of the flight programs was to find icing, especially with high LWC. This also resulted in a gross underestimate of the frequency of "null" icing conditions (SLWC=0 gm^{-3}; 20.1%). Relatively unbiased measurements, such as those taken by TAMDAR probes flown on commuter aircraft around Minneapolis, Detroit and Memphis show that icing is absent during ~93% of flight time during the same three-month period (Braid et al. 2006).

7. PERSPECTIVE AND FUTURE WORK

Some minor changes to the algorithm and the severity thresholds are still under consideration. Readers and product users should remain aware that due to the large variety in aircraft types, flight configurations and level of pilot experience, there will be a good deal of overlap between reported severity categories. Thus, even if CIP Severity diagnosed the LWC, drop size and temperature perfectly and translated them into a severity metric, the aircraft and pilot factors will result in a variety of reported severities within a given meteorological environment. Differences between diagnosed and reported severity within about one severity category (e.g. a light PIREP in an area where conditions are diagnosed as moderate) are to be expected, as seen in Fig. 4b

While many candidate fields were tested as part of the development process, there were also many that could not be implemented into this version or that were not part of this test. Chief among these are the satellite products being developed by the NASA-Langley Research Center, which have shown promise when ingested into the high-resolution version of CIP

(HRCIP; Haggerty et al. 2005). Three-dimensional radar mosaic data (Elmore et al. 2004) may provide more detailed vertical information on precipitation location and intensity, which may be a significant improvement over the 2-D mosaics currently employed by CIP.

Recent verification exercises have shown that CIP icing diagnoses maintain considerable skill for several hours after their valid time. Thus, persistence information from recent CIP runs may prove useful, especially in periods where dataset confidence is changing rapidly, such as near the solar terminator, but the conditions are reasonably consistent.

One area of promise is a more meteorologically-based mapping of PIREP and METAR observations using object/pattern matching. This concept is currently being tested via similarity analysis of satellite observations, and could be extended to include radar observations and numerical model output (e.g. theta-e and wind fields). Such an analysis may provide developers with more confidence information on PIREPs and METARs, both spatially and temporally. It may allow for these observations to be applied more broadly across areas with consistent features, and more carefully where gradients are present. PIREP observations on cloud top height used in this context may help to improve CIP's cloud top height estimates.

A FIP Severity product is also under development and scheduled for AWTT board consideration in 2007. It will make use of much of the CIP Severity development work, taking advantage of model-derived fields that have proven to have value for icing severity (e.g. vertical velocity). Attempts will be made to mimic some observation-based parameters, such as radar reflectivity, coupled with expected precipitation type.

8. CONCLUSIONS

The new version of CIP Severity has been designed to estimate SLWC and thus, icing severity, based on cloud physics principles, forecaster experience and knowledge of the strengths and weaknesses of the datasets readily available in an operational setting. Exhaustive testing of ~200 variables considered to be potentially valuable for the diagnosis of icing severity was completed and only a small subset of these variables was included in the final algorithm. These fields were derived from satellite, radar, surface, lightning and pilot observations in combination with numerical model output, including explicit microphysics predictions. Fuzzy logic membership functions have been applied to these fields in a scenario-based approach to make appropriate use of the information.

CIP now outputs five categories of icing severity: null, trace, light, moderate and heavy. If this field shows adequate skill in upcoming verification tests, the product could reach operational status by winter 2006-07. With an hourly diagnosis of icing severity, a calibrated icing probability field and an indication of the likely presence of supercooled large drops, it is hoped that the audience which this product reaches for decision making purposes will be extended to include pilots. The product may also prove useful to forecasters making AIRMETs and SIGMETs, especially when the experimental forecast version (FIP Severity) comes on-line in the same time frame. FIP Severity is slated for operational status in winter 2007-08, pending AWTT Board approval.

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