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ISSUES IN FORECASTING ICING SEVERITY

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1. INTRODUCTION

Forecasting icing severity is one of the more difficult jobs in aviation weather. One has to forecast a poorly-defined condition (current severity definitions are based on an airplane and pilot's response to the icing environment), using inadequate information (no direct measurement of cloud liquid water content). However, aircraft operating requirements force the issue and we must find a way to do this satisfactorily.

There is no requirement to accurately forecast liquid water content; the requirement is to determine areas of moderate or greater icing, and of severe icing conditions. Aviation weather forecasters commonly examine icing pilot reports (PIREPs) in context of the current weather, and extrapolate their severity along with the weather features. This is a reasonable approach, but it has not been verified for accuracy. Are there better approaches to predicting expected icing severity? NCAR is working on inclusion of severity in automated icing diagnosis and forecast products that meet user requirements, and progress on this daunting task will be presented.

2. DEFINING SEVERITY

Table 1 lists definitions currently in the approval process for inclusion in the Airmen's Information Manual (AIM). These are simplifications of current icing severity definitions, but note that they are intended for pilots reporting icing conditions to the ground via a PIREP rather than guidelines for forecasters. Note that the recommendation is to replace the word "severe", in current use, with "heavy".

Attempts at definitions of icing severity in terms of weather parameters use liquid water content, static air temperature and droplet size as the most relevant parameters in that order. Lewis (1947), Newton (1968), Jeck (1992) and Politovich (1996) offered various refinements to a definition based on the accretion of ice on a 3-in cylinder moving through the atmosphere at 200 kt perpendicular to its axis. This cylinder has traditionally been considered a reasonable standard, and the application to individual aircraft was up to the user.

Table 1: Icing Severity Descriptions

Category	Description
Trace	Ice becomes noticeable. Rate of accumulation is slightly greater than the rate of sublimation.
Light	The rate of ice accumulation may require occasional use of ice protection systems to remove/prevent accumulation.
Moderate	The rate of ice accumulation is such that frequent use of ice protection systems is necessary.
Heavy	The rate of ice accumulation is such that ice protection systems fail to remove the accumulation of ice.

The LWC thresholds using this system are: light 0.1 g m^{-3}, moderate 0.6 g m^{-3}, and severe 1.2 g m^{-3} for 15-μm droplets (the thresholds are lowered for larger droplets). Jeck (1998) recently proposed a different system based on the time it takes an airfoil to accrete 1/4 inch of ice on its leading edge. This was considered an amount that a pilot could easily see from the cockpit, with the idea that accretion of this amount could be roughly timed by the pilot prior to inflight deicing. It has the additional advantage of being quantifiable. If the accretion time is known, assumptions are made concerning the ice density, and the aerodynamic properties of the airfoil are known, the liquid water content necessary to produce the desired accretion rate could be calculated. The calculations are quite dependent on droplet diameter assumed since that dictates the collection efficiency on an airfoil; this affects the higher severity categories much more than the lower ones (Fig. 1). According to Jeck (1983), a 15-μm droplet is a reasonable assumption for most clouds, since his extensive data set obtained in icing conditions shows that ~75% of all measurements have droplet mean or median volume diameters within 5 μm of that value.

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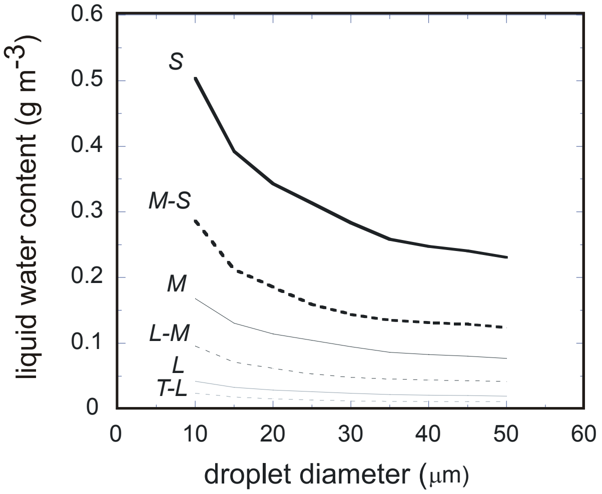

Fig. 1: Severity definitions according to time to accrete 1/4 inch of rime ice on a variety of airfoils, as a function of droplet diameter. Categories are as follows: TL=trace-light, L=light, L-M=light-moderate, M=moderate, M-S=moderate-severe, S=severe and heavy.

Both attempts at defining icing severity omit perhaps the most important consideration, that is, the actual decrease in performance of the aircraft. Different aircraft in different flight configurations will respond differently to similar accretions of ice. Accretion models have undergone extensive testing and verification using natural cloud or icing wind tunnel data (*cf.,* Wright and Rutkowski, 1999 for a summary of the LEWICE model). Performance assessment models are at best in early stages of verification but the general agreement of the icing community is that they are not yet at a mature enough stage to be run routinely for a variety of aircraft types representing realistic conditions.

3. PREDICTING LIQUID WATER CONTENT

To examine the feasibility of using Rapid Update Cycle (RUC) model-generated condensate fields to predict icing severity, we examined 63 3-h forecasts from 22 days between 10 March and 23 May 2001. These were experimental RUC-20 runs conducted by the NOAA Forecast Systems Laboratory (FSL) in preparation for the operational implementation of this new model version at the National Center for Environmental Prediction.

Over 2,600 pilot reports of (positive) icing were used in the comparison; all severities were included. For the comparison, each PIREP within 1 h of the valid model forecast time was located in the model grid, and a 6x6 horizontal (same hybrid-b surface) box surrounded the report. Vertically, all 6x6 stacked boxes within 1500 ft of the reported PIREP altitude were used. The maximum (minimum for vertical velocity) value of the comparison parameter within the collection of grid points was used to compare with the icing PIREP.

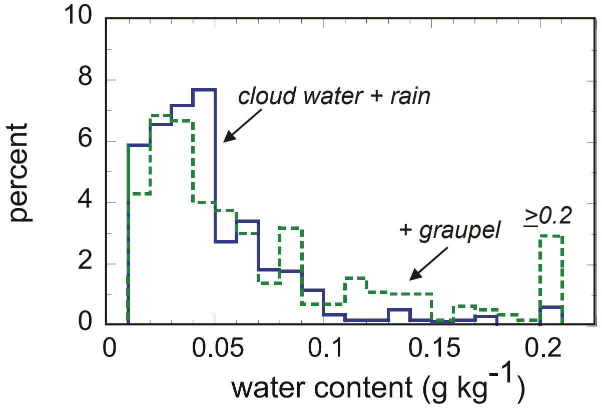

Fig 2: Frequency of condensate predictions from the RUC-20 matched to icing PIREPs. Condensate values of zero are not included and are 59% for cloud liquid + rain, and 56% with graupel added.

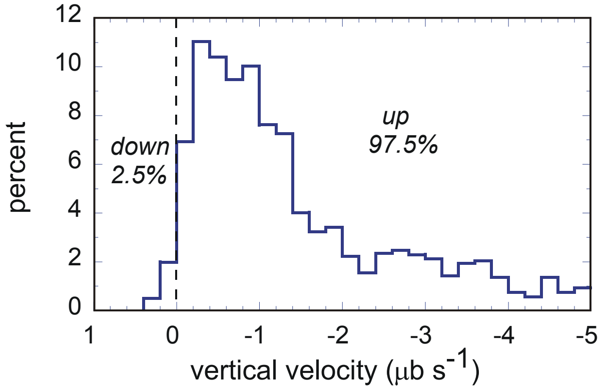

Fig 3: Frequency of vertical velocity predictions from the same forecast comparison set as Fig. 2.

Condensate was divided into two categories: cloud water plus rain, and cloud water and rain plus graupel (see Fig. 2, all cloud water and rain are subfreezing). Graupel is formed by riming of cloud water and rain onto snow and ice; it indicates where supercooled liquid has resided and thus may help pinpoint where icing ought to be. For cloud water and rain, 59% of the PIREP-matched grid points had values of zero. Inclusion of graupel reduced this by 3% to 56%. Inclusion of snow and ice improved this value to 26% (not pictured), with also a higher percentage of values >0.2 g kg^{-1} (24%). However, since the physics of the ice nucleation and growth processes is vastly different than those of cloud water and rain (in reality as well as the model parameterizations), it does not seem reasonable to include these in quantification of the supercooled liquid water field, although they could be used to identify cloudy areas. PIREP position and altitude reporting errors are not likely to be the source of the lack of matching to model clouds, given the generous allowance made for location of the PIREPs in the model domain.

Vertical velocity might be used for helping to identify clouds where liquid is expected in upward-moving air. The distribution for the same sample set used for the condensate comparisons shows is skewed very much toward upward motions (Fig. 3). This indicates that the RUC-20 can indeed predict the upward motion associated with the formation of icing conditions, but the microphysics parameterization frequently mis-categorizes the condensate type as snow or ice crystals rather than liquid water.

Condensate predictions from this version of the RUC model have not yet been quantitatively verified. To date, such comparisons have been disappointing (as in Guan et al., 2001). We are in the process of archiving the FSL experimental RUC model output to compare with data collected using the NASA Glenn Research Center Twin Otter, which is flying icing research missions in the Cleveland, OH area during February and March 2002. However, the fact that a considerable fraction of icing PIREPs have no condensate (especially liquid) associated with them is not encouraging for attempting severity forecasting from a liquid water quantification, such as using the schemes described above.

4. ANOTHER METHOD

The AWC has developed an experimental icing forecast product, VVICE (McCann, 1998, 2000) with an output of expected percent power increase needed to maintain airspeed for level flight. While the concept is a step in the right direction, the current product suffers from several problems. Sub-gridscale vertical motions are applied to produce local lifting above that expected for the model resolution (currently 40 km), to simulate "worst case" conditions within the model grid area. Cloud physics equations representing production of liquid water and droplet growth from enhanced lifting are applied, but it is not clear whether realistic depletion processes are included. Thus a cloud that may be producing copious amounts of ice and possibly glaciating would be considered an icing hazard. The same would be true for a cloud that produces liquid water which is subsequently depleted by “seeding” by ice crystals falling through the cloud from aloft. The accretion and performance are based on drag calculations for a standard NACA 0012 airfoil. The output is in terms of increased power required after 15 min of flight. However, in that time the target airfoil flying at the assumed 80 m s^{-1} travels 72 km. This is longer than the model grid spacing, and much longer than the subgrid-scale vertical motions upon which VVICE is constructed. One cannot expect subgrid "worse case" conditions to persist within the entire grid point area. The average LWC for that grid space may be the more appropriate value to use.

5. A SCENARIO-BASED APPROACH

The Integrated Icing Diagnosis Algorithm (IIDA, see McDonough and Bernstein, 1999) is physically based on the identification of certain weather scenarios conducive to inflight aircraft icing. This implies the presence of supercooled liquid water, but the construction of the algorithm is meant to determine the likelihood of icing rather than the expected severity. However, a similar scenario-based approach may be appropriate for severity determination.

Through a combination of basic cloud physics principles, forecasting experience, and analysis of inflight measurements, we can identify certain types of cloud-forming processes that are conducive to high or low amounts of supercooled liquid water contents. These scenarios can then be translated to the observations and model outputs available for the algorithm. Briefly, we are linking cloud types, and weather scenarios associated with them, to their potential to provide a source of supercooled liquid water through both production and depletion processes.

<u>Cirrus</u>: identified by height (model or satellite-determined). These are cold, thin clouds -- from base to top -- containing primarily ice crystals and perhaps miniscule amounts of liquid water. They can also be identified specifically using multi-spectral GOES data. They are considered trace icing at most.

<u>Cumulus</u>: identified by instability and non-uniformity in observed and model fields. Model output, satellite imagery, surface observations and precipitation pattern will be used to distinguish these. Further details on whether the cloud is a mature/maturing Cb, a young Cb, or a capped Cu or Sc layer (according to layer depth, temperature and air mass source) may be used to estimate icing severity potential. For example, relatively warm Sc with little or no precipitation and relatively warm tops can contain high (in some cases nearly adiabatic) amounts of LWC and occasionally SLD. Isolated mature Cb with heavy precipitation are generally more glaciated and thus much less an icing threat (although aircraft penetration is not desired for other obvious reasons).

<u>Stratus</u>: identified by uniformity in satellite features (*e.g.*, IR temperature) and precipitation, and reside in generally neutral or stable environments. Can be significant icing threats if warm (tops <~-12 to - 15^{o}C) and associated with little or no precipitation. On the other hand, stratus that is cold throughout producing snow beneath probably present a lower severity threat.

<u>Orographic clouds</u>: identified by association with terrain. The terrain effects may modify already-existing stratiform or cumuliform clouds. Thin cap clouds typically have low liquid water contents. Deep lenticular clouds, such as those occasionally situated downwind of the Rockies, sometimes contain significant amounts of liquid as evidenced by the icing PIREPs at relatively high altitudes (>~16,000 ft) observed from them. Anecdotal evidence suggests that strong upward vertical velocity is present in the model output for such

cases. These clouds can also have satellite features similar to glaciated orographic clouds; additional information is needed to distinguish them.

This approach is being formulated and is much more complex than described here. However, based on our and others' experience using these approaches manually when forecasting, we expect that it will prove successful. A similar approach has performed quite well for identifying the potential for supercooled water to exist at all, which is the current output product of our automated algorithm.

6. STATISTICAL METHODS

The Integrated Turbulence Forecast Algorithm (ITFA, see Sharman et al., 2000) uses a dynamic weighting approach. Current PIREPs of turbulence are matched to carefully-chosen metrics calculated from current model outputs. The best performers are weighted and applied to model forecast fields to predict future turbulence and its severity. This approach has some appealing aspects, especially considering it's what many forecasters do to predict severity. The key is to choose the metrics carefully, making sure they have a physical basis. We are considering such an approach for icing severity forecasting and are looking into combining it with extreme analysis techniques. Icing is by its nature a rare and somewhat extreme atmospheric event (typically <~14% of the total airspace above the CONUS at any given time, as in Brown et al., 2001), and severe icing represents an even more extreme situation (~3% of all icing reports, as in Shultz and Politovich, 1992). The statistics for such events differ enough from more "normal" conditions that this is probably a more appropriate approach for icing.

7. SUMMARY

We have outlined several approaches to include severity in automated diagnoses and predictions of inflight icing. During the next year we will implement one or more of these for testing. We will convert the outputs to fuzzy logic interest fields to match the physically-based methods already used in the algorithm. Thus the information each approach provides can be optimized to produce a quality forecast of icing severity that can be used by the flying public. The eventual goal is to pair a weather simulation model with an aircraft performance-accretion model and forecast the capability of a specific aircraft flying through predicted weather conditions.

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