3.2 THE FORECAST ICING POTENTIAL (FIP) ALGORITHM

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1. Introduction

In-flight icing is a serious hazard to the aviation community. It occurs when subfreezing liquid cloud and/or precipitation droplets freeze to the exposed surfaces of an aircraft in flight. Icing conditions can occur on large scales or in small volumes where conditions may change quickly. Because of the nature of icing conditions, the need for a forecast product with high spatial and temporal resolution is apparent.

The FIP (Forecast Icing Potential) algorithm was developed at the National Center for Atmospheric Research under the Federal Aviation Administration's Aviation Weather Research Program. It uses 20-km resolution Rapid Update Cycle (RUC) model output to determine the potential for in-flight aircraft icing conditions and supercooled large drops (SLD; defined as droplets with diameters greater than 50μ). Forecasts are created every 3 hours and are valid 3, 6, 9, and 12 hours after the run time.

2. Algorithm Input

The CIP (Current Icing Potential; Bernstein et al., 2004) algorithm serves as the template for FIP. CIP combines observations from satellite, radar, METARs, and pilot reports of icing (PIREPs) with RUC model output to calculate an icing diagnosis every hour. Because such observations are not available in a forecast mode, FIP must create surrogates for these observations from the model to build its forecasts. This section will explain how FIP emulates the observations from model data.

a) Cloud Scheme

The FIP cloud forecast scheme begins by examining each model column, starting at 300mb and working downward. It searches for the first model level with a relative humidity with respect to water (RH) of ≥ 70%. This level is designated as the highest cloud top and the corresponding temperature as its cloud top temperature (CTT). The 70% threshold was chosen to allow for expected model moisture errors and to allow for cold clouds to be found without a model forecast of water saturation. The use of a combination of relative humidity with respect to both water and ice may allow for the use of a higher threshold in future versions of FIP.

Cloud base is found by working upward in the same column until the first level with RH≥80% is found. Since the model boundary layer often has RH>80%, even in cloud-free air, FIP begins its search for a cloud base at 1000ft (305m) AGL. The threshold of 80% for cloud base identification is used to also allow for model moisture errors and the expectation that cloud base is found at warmer temperatures where RH and RHi are more equivalent. A column is determined to be cloud-free (and icing free) if the RH values are <70% from 1000 ft. AGL to the tropopause.

Multiple cloud layers can also be identified by examining the column of RH values. FIP searches for at least three consecutive vertical levels with RH < 50%, surrounded by two moist (RH>=70%) layers. Such a dry layer is likely to prevent precipitation falling from the upper cloud to sublimate/evaporate before reaching the lower cloud layer. The cloud layers above and below the dry air will be treated as independent clouds for later determination of the potential for icing. All cloud layers identified are assigned their own cloud top and base altitude and temperature.

b) Precipitation

If the model quantitative precipitation forecast (QPF) is ≥ 0.1 mm in 3 h, the FIP grid point is expected to have precipitation that reaches the surface. Using an augmented version of the Baldwin et al. (1994) scheme, the precipitation type is determined to be rain (RA), snow (SN), freezing rain (FZRA), ice pellets (PE), drizzle (DZ) or freezing drizzle (FZDZ) see example in Fig. 1. Rain typically forms when snow falls through a warm layer (T>=0°C) and to the surface where T>=0°C. Freezing rain and ice pellets form in the same way but fall into a surface-based layer with T<0°C after falling through a layer of warm air. FZDZ and DZ were added to the precipitation type scheme by identifying precipitating clouds with CTT>=-8°C and checking the surface temperature.

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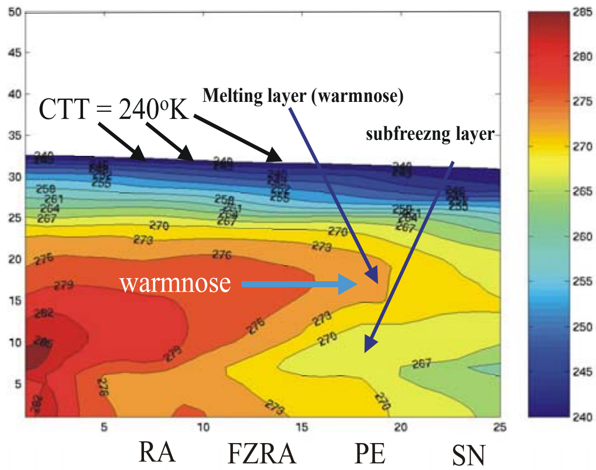

Figure 1. Vertical temperature °K cross-section of 25 RUC model grid points with expected surface precipitation type noted.

Precipitation falling from clouds with such warm tops was likely formed by the collision-coalescence process, resulting in FZDZ or DZ at the surface, depending on the surface temperature. Any of the precipitation types, except SN, may be associated with the presence of liquid precipitation and the possibility of icing below the cloud base. If SN is determined to be the precipitation type in the layer below cloud base, then icing is not expected there.

3. Interest Maps

FIP combines the model input data using fuzzy logic membership functions and a decision tree to estimate the potential for icing. The membership functions are based on cloud physics principles, forecasting and research experience, and comparison of fields to icing PIREPs. They map data onto a 0-1 scale, which represents the expected likelihood of icing, given the value from that field.

When clouds are expected to be present, the temperature, relative humidity and cloud top temperature membership functions are situationally applied to estimate the initial potential for icing. The vertical velocity, explicit supercooled liquid water (SLW), and precipitation rate membership functions are then used to either boost or lessen the initial icing potential, if it was non-zero. All of the functions are intended to mimic the interest that a human forecaster would have when applying the field to an icing forecast. For example, an RH of 90% is more likely to likely to be associated with icing than an RH of 75%, given that all other conditions remain the same. The full details of most of these maps can be found in Bernstein et al. (2004). A brief summary will be provided here.

a) Temperature

Icing conditions are most common at temperatures close to freezing and become less likely with decreasing temperature, because the chance of significant ice crystal concentrations increase (Rogers and Yau, 1989; Rauber et al., 2000). Icing is relatively rare at temperatures below –25°C. The temperature membership function ($T_{\mathbf{map}}$;Fig.2) was built with these factors in mind. $T_{\mathbf{map}}$ also takes into account compressional heating on the leading edge surfaces of an aircraft. This is the reason for the sharp decrease in interest as the temperature increases from –4°C to 0°C even though SLW is very likely at these temperatures.

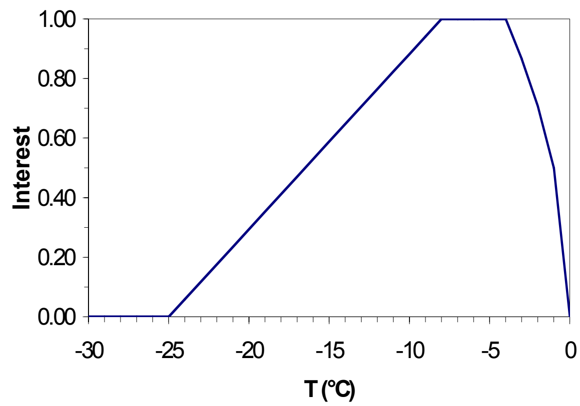

Figure 2. FIP $T_{\mathbf{map}}$ membership function for temperatures from –30 to 0°C.

b) Cloud Top Temperature

Because temperatures within a cloud layer are normally coldest at its top, cloud top temperature (CTT) can have a large effect on the chances for icing throughout a given cloud's depth. If cloud tops are cold enough to produce copious amounts of ice crystals, those crystals are expected to fall through the remainder of the cloud layer below, resulting in partial or complete glaciation. Warm-topped clouds are likely to be dominated by liquid water, causing no glaciation below. This concept is reflected in the CTT membership function ($CTT_{\mathbf{map}}$; Fig. 3).

CTT_{map} is set to 1.0 for CTT>0°C since such cloud tops will consist entirely of liquid, and remains 1.0 down to –12°C, because these tops are also likely to be dominated by liquid water droplets. CTT_{map} drops off with decreasing cloud top temperature, as cloud tops are more likely to be dominated by the ice phase. CTT_{map} never becomes zero, even at very cold temperatures. Instead, it reaches a lower limit of 0.2 for CTT colder than -50°C. While very cold cloud tops certainly imply the presence of copious amounts of ice, the production of liquid water may exceed the depletion by scavenging in parts of the cloud, often due to strong lifting. Therefore, the icing potential cannot be completely shut off due to a low CTT.

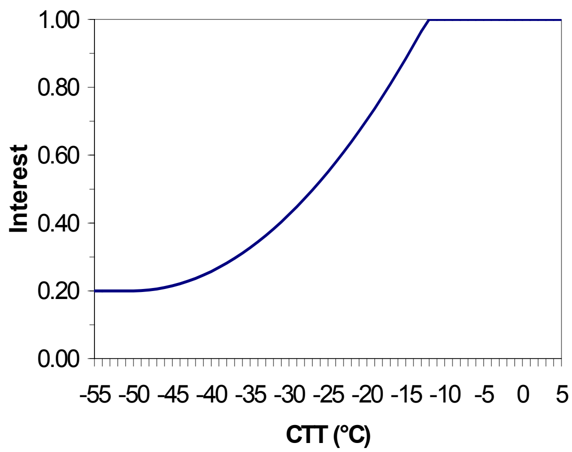

Figure 3. FIP CTT_{map} for cloud top temperatures from –55 to 5 °C.

c) Relative Humidity

The FIP relative humidity map (RH_{map}; Fig. 4) represents the confidence that clouds (and thus, a chance for icing) are present between the cloud top and cloud or precipitation base. Ideally, the RH_{map} would be set to 1.0 for RH values of saturation only (100%) and 0.0 for all other values. However, moisture is a difficult field for the models to predict (Wolff, 2004) RH_{map} is generous. Distributions of positive icing PIREPs with model relative humidity have shown that icing is often reported with RH well below 100%. RH_{map} takes this into account, with interest beginning at 30%, growing slowly to 0.1 at 60%, and then ramping up quickly to a value of 1.0 at 95%.

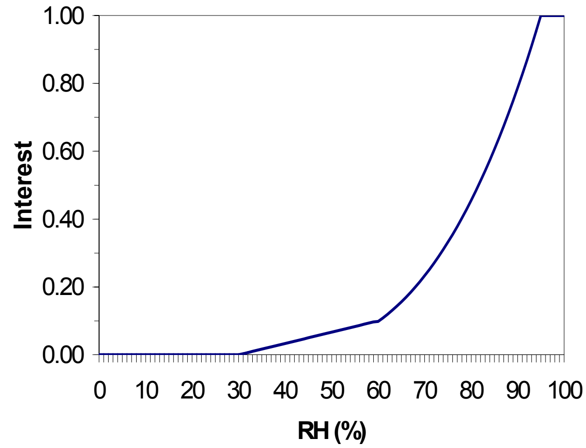

Figure 4. FIP RH_{map}.

d) Vertical Velocity

At this point, output from CTT_{map}, T_{map}, and RH_{map} at each three-dimensional cloudy or precipitating grid point is typically multiplied to estimate the initial icing potential. If this field is non-zero, then information from the vertical velocity, model SLW and precipitation rate fields are applied to increase or decrease it.

Upward vertical motion lifts air, cools it, and increases its relative humidity, implying a stronger chance for SLW production. Downward vertical velocities tend to cause clouds to dissipate and SLW to decrease. Politovich et al. (2002) showed that 74% of icing PIREPs occur in rising air motions forecast by the RUC. The vertical velocity membership function (VV_{map}; Fig.5) reflects this, with positive (negative) interest for upward (downward) motion..

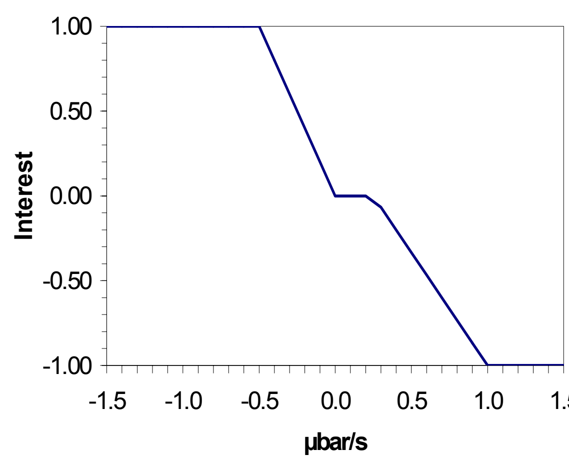

Figure 5. FIP VVmap. Negative VV values represent upward vertical motion.

e) Supercooled Liquid Water

RUC model explicit predictions of SLW have been shown to capture ~40% of positive icing PIREPs, while covering a very small volume of airspace, making it very efficient (Brown et al., 1997; Politovich et al., 2002). Though it cannot stand alone as an icing predictor, a forecast of explicit SLW can increase a forecaster's confidence that icing will be present. Thus, the SLW field is very useful as a boosting factor, but the lack of predicted SLW can not be used to decrease the chance for icing. The SLW interest map (SLW_{map}; not shown) reflects these characteristics by placing a high confidence in areas where the model predicts SLW and a neutral interest where the model has no SLW. SLW_{map} is 1.0 where the model forecasts SLW and 0.0 elsewhere. Positive values of SLW_{map} boost ICPOT and the zero values leave it unchanged.

f) Precipitation Rate

The QPF interest map (Fig. 6) is applied differently for different precipitation types. It assumes that higher precipitation rates suggest a more efficient precipitation process aloft. If SN is forecast, then a higher QPF implies an efficient ice process and lower chance of icing. Conversely, if FZRA is forecast a high QPF increases the interest due to more freezing rain falling through the lower parts of the atmosphere.

4. Meteorological Situations

There are many ways for SLW to form in the atmosphere. FIP uses a decision tree to determine the thermodynamic structure (situation) for each column and applies the model information in the appropriate way. Each piece of information is valuable, but can mean different things in different icing situations. By using this physically based, situational approach, along with appropriate use of the membership functions, FIP determines icing and SLD potentials at all locations in the RUC grid. This section presents some of the basic icing scenarios that FIP identifies and how the algorithm uses the given information to come up with an initial icing and SLD potential. Boosting factors are applied later.

a) Single-layer non-precipitating clouds

This is the most basic situation for the algorithm. The example case in Fig. 7 demonstrates a grid box with a single cloud layer of constant thickness and CTT, with the entire atmosphere below freezing. Temperatures in the cloud range from –1 °C at the base to –8 °C at the top. The model predicted RH values are high (> 90%) throughout the cloud depth. The combination of ideal icing temperatures, CTT, and RH result in a high icing potential (ICPOT) from the cloud top down to the –4°C level. As the temperature warms in the lower part of the cloud layer the icing potential decreases due to the lower T_{map} values. Icing potential is set to zero above cloud top and below cloud base. There are no direct indicators of SLD (i.e. no surface precipitation) so the SLD potential field is set to "unknown" within the icing layer and zero elsewhere. Although icing is forecast and there is no indication that this cloud layer is producing SLD, the possibility of SLD aloft cannot be ruled out.

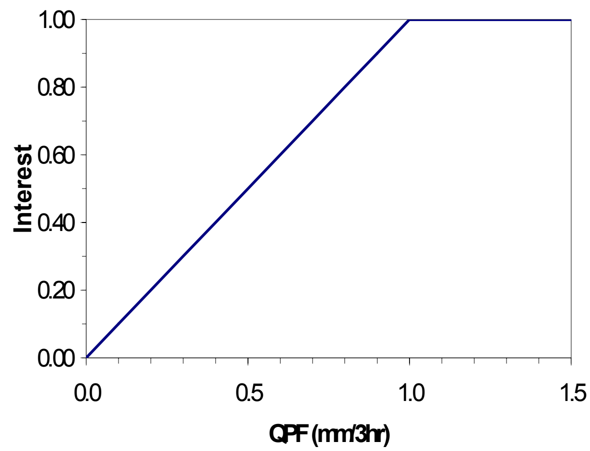

Figure 6. FIP QPFmap.

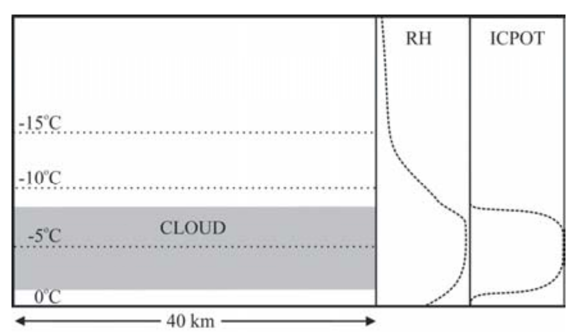

Figure 7. Conceptual diagram of a non-precipitating, single-layer icing cloud deck.

b) Single-layer precipitating clouds

This situation is similar, except that precipitation is falling from the cloud. When freezing precipitation is forecast, the precipitation is likely to be formed by collision-coalescence and the icing potential is quite high. SLD is also expected at least up to the cloud base and probably well into the cloud.

If SN is forecast at the surface then ice crystals are present within the cloud, scavenging SLW as they fall. FIP will decrease the icing potential somewhat by using a snow factor to account for the depletion of SLW. However, with the warm cloud top and ideal values of T and RH in the cloud the icing potential will still be relatively high. The potential will be lowered somewhat by including the precipitation rate in the equation (see Section 3f).

If the surface is above freezing and DZ or RA is forecast, the precipitation could be formed either via melting or collision-coalescence aloft, depending on the CTT of the lowest cloud layer. If the cloud top temperature is relatively warm (cold), then liquid (ice) processes are likely to dominate, and collision-coalescence (melting) is likely the formation mechanism for the drizzle or rain. If CTT<–12°C FIP sets the SLD potential to "unknown" since the precipitation was most likely formed by an ice process.

c) Multiple Cloud Layers

In this case, two cloud layers have been identified by FIP, and they are treated independently. The lower cloud (with CTT=-8°C and no precipitation falling out of it in this example; Fig. 8) is similar to the cloud layer discussed in Section 4a, with high icing potential due to its ideal T, CTT and RH. Because of the very cold T and CTT, the icing potential is zero throughout most of the upper cloud layer, except where T>–25 °C.

d) Classical Freezing Rain Structure

Freezing rain most often occurs when snow, formed in a deep cold-topped cloud, falls through a melting layer, then into a layer with T<0^{o}C (Fig. 9). FIP uses the RUC vertical temperature structure to divide the column into two levels: above and below the melting layer. The upper layer is treated like a single layer cloud. The layer below the melting layer is likely to contain icing and SLD because of the melting process and expectation of freezing rain at these levels. Only the T_{map} is used to calculate icing and SLD potential in this layer, since they are not related to CTT or RH there. Higher values of QPF will also increase these potentials because this indicates more large drops falling through the layer. In the example shown in Fig. 9, the icing and SLD potentials are high in the subfreezing layer beneath the melting layer, and zero in the melting layer due to the above freezing temperature. Above the melting layer there is low icing potential because the T and RH values are ideal, but CTT is very low. The presence of strong upward vertical velocity or model predicted SLW could boost the icing potential in this layer. SLD potential is set to "unknown" here because, while SLD cannot be ruled out there is nothing to indicate its presence in this layer because it is treated separately from the lower layer and the surface.

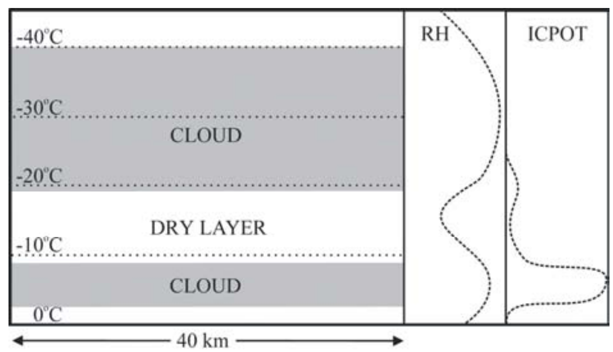

Figure 8. Conceptual diagram of a cirrus deck overlaying a low stratus deck, with a deep dry layer in between.

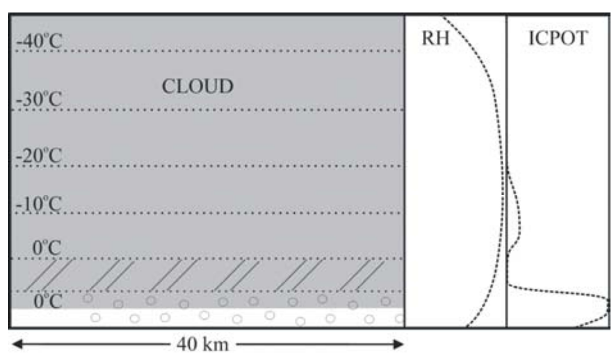

Figure 9. Conceptual diagram of a classical freezing rain situation.

5. Summary

The FIP uses a decision tree and fuzzy logic to combine information from RUC model fields and produce a forecast of the potential for icing and SLD conditions to exist across the model domain (CONUS and southern Canada). While FIP provides good quality icing forecasts that have proven to be of value to pilots and dispatchers, there is room for improvement. Future upgrades include; the implementation of an icing severity algorithm, and identification of convective icing situations and addition of a cloud base temperature membership function.

6. References

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