13.5 Forecasting Supercooled Large Drop Conditions

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1. Background

Aircraft icing has been recognized as an in-flight hazard since the 1930s, following the earliest instrumented flights into sub-freezing clouds. In the 1940s a series of research aircraft flights were conducted to document the range of icing conditions found in the atmosphere. Analysis of these research flight data led to the creation of the FAR 25 Appendix C icing envelope in the 1950s (gray shaded area of Fig. 1).

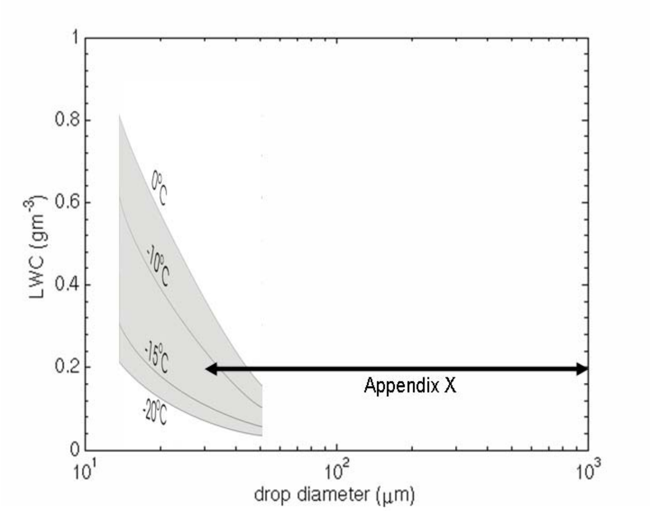

Figure 1. The Appendix C icing envelope for intermittent icing (gray shading), Appendix X represented by heavy black line.

To this day aircraft must conduct successful flight tests within Appendix C icing conditions to be certified to fly in subfreezing clouds. The 1940s research flights also encountered a few icing clouds containing supercooled large drops (SLD), drops with diameters ≥ 50 μm, but these conditions were thought to be rare and weren't included in the envelope. Therefore the maximum drop sizes within Appendix C are 40μm for continuous icing conditions and 50μm for intermittent icing conditions. With the advent of new research aircraft cloud particle probes in the 1970s an era of better observations of cloud particles began (Heymsfield and Parrish 1978).

Sand et al. (1984) and Politovich (1989) observed an increased loss of aircraft performance when icing clouds contained SLD. This loss of performance was in part due to the accretion of, and inability to remove, ice beyond the de-icing boots. The boots were designed for Appendix C icing, which tends to form along the leading-edge of the wings. In 1994 an ATR-72 holding in SLD icing conditions near Chicago, IL crashed killing 68 people (Marwitz et al. 1997). In 1997 an EMB-120 crashed on descent into Detroit, MI killing all 29 people on board. Heavy freezing drizzle was observed at the surface by the author ~100km south of, and several hours before, the accident. These accidents led to an increased focus on the meteorology of SLD icing. The results of several field campaigns (Isaac et al. 1999, Miller et al, 1998) and icing climatologies (Bernstein et al. 2007) have shown that SLD was more common than the 1940s research icing flights associated with Appendix C indicated. An SLD extension to Appendix C, Appendix X has been suggested (see black line in Fig. 1). Since most aircraft operating in icing conditions have not been tested for flight in SLD icing conditions a method to forecast and identify these conditions is required. This paper presents a method to forecast in-flight SLD icing conditions using numerical model soundings.

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2. Formation of supercooled large drops

SLD forms in the atmosphere in one of two ways. The so called ‘warm rain’ process (Huffman and Norman 1987) occurs as an all water process in subfreezing clouds. Cloud drops form through condensation then grow to sizes where collisions with other drops become likely. The other formation mechanism is the so called ‘classical’ freezing rain process. These are deep clouds in which snow forms in the upper cold regions of the cloud. The snow falls into an elevated warm (temperature > 0°C) layer and melts into liquid drops. The drops then fall into a sub-freezing layer where they supercool, without re-freezing.

2.1 Collision-Coalescence

SLD formation via the warm rain process generally requires a warm cloud top temperature (CTT). Geresdi et al. (2005) showed that 90% of freezing drizzle (SLD with diameters > 100µm) reported at the surface near sounding stations formed in collision-coalescence clouds with CTT > -12°C. SLD-forming clouds sampled by research aircraft also often had warm CTTs (Politovich 1989, Rasmussen et al. 1995, Cober et al. 1996, McDonough and Bernstein 2004). The warm cloud top temperatures suppress ice crystal formation which would favor drop growth by collision-coalescence. Increased concentrations of larger ice crystals in colder clouds, increases the probability of ice-large drop collisions, thus reducing the icing threat.

Examination of the microphysical structure within cloud layers over the southern Great Lakes showed that SLD was more likely to form within ‘clean’ clouds, those with low concentrations of small drops (Bernstein et al. 2004). Analysis of the thermal and microphysical vertical structure of many the Great Lakes clouds suggested that SLD formed in moderate liquid water contents (LWCs) within the clean air. Clean was defined as air that was detached by an inversion or isothermal layer from the boundary layer. SLD did form within high droplet concentration boundary layer clouds but only when the liquid water content was large (> 0.5 gm^{-3}).

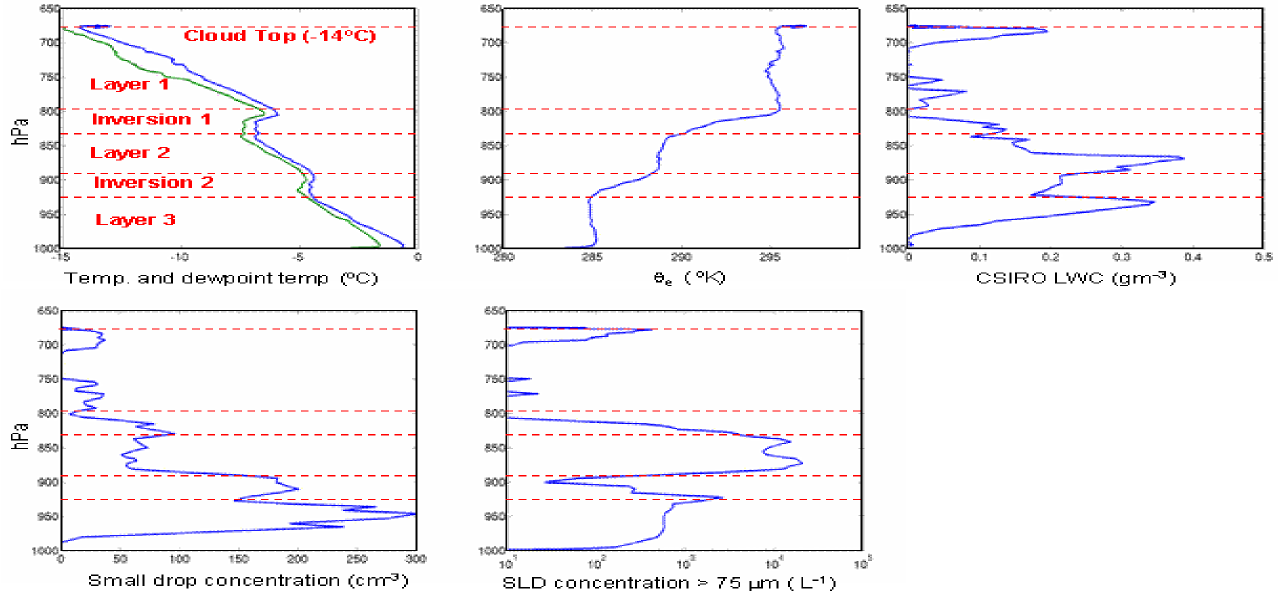

Figure 2. The vertical profile of the KGRB SLD icing cloud. T/Td, θ_e, LWC, cloud drop concentration, SLD concentration > 75µm.

Figure 2 shows the vertical structure of the SLD cloud documented by McDonough and Bernstein (2004). Three distinct cloud layers, isolated by inversions, were clearly identified in the temperature/dew point temperature and θ_e profiles. The top of Layer 1 had a LWC maximum (> 0.2 gm^{-3}) distributed over a very low drop concentration of 30 cm^{-3}, with a CTT of -14°C. The ice crystal concentrations were < 1 L^{-1}. SLD in concentrations exceeding 500 L^{-1} formed near the top of the layer. Layer 2 had LWC exceeding 0.4 gm^{-3}, distributed over 60 drops per cm^{-3}, with a layer top temperature of -7.5°C. No ice phase was observed within this layer and SLD in concentrations > 10^4 L^{-1} formed. Layer 3, the boundary layer, had a layer top temperature of -4°C and moderate LWC (> 0.3 gm^{-3}) distributed over a much higher 300 drops cm^{-3}. SLD was present in Layer 3 but the size distribution (not shown) and previous studies (e.g. Bernstein et al. 2004) suggested that the SLD initially formed in Layer 2 then seeded Layer 3. This case study shows the importance of low drop concentrations in the production of SLD.

Along with many other aviation hazards, deep convection often produces a significant icing threat to anomalously cold temperatures. SLD rapidly forms within the strong undiluted updrafts and their associated high supersaturations.

2.2 *Classical freezing rain*

The vertical structure of the clouds producing freezing rain has been well documented (e.g. Martner et al, 1993). As previously mentioned, the thermal structure requires a deep cold cloud top, melting layer aloft, and a low-level subfreezing layer. Figure 3 shows an example of a classical freezing rain sounding during the 1998 southeastern Canada ice storm. Ice crystals initially formed in the cold cloud tops. These crystals grew as they fell through the ice-saturated upper cloud. Eventually the snow melted into rain drops within the warm, above freezing layer between 780-900mb. The rain drops then supercooled as they fall into the subfreezing layer below 900mb. Along with damaging surface icing, this event created a significant SLD in-flight icing hazard below 3,000ft. Bernstein et al. (1999) showed an example of dangerous SLD icing formed by this process.

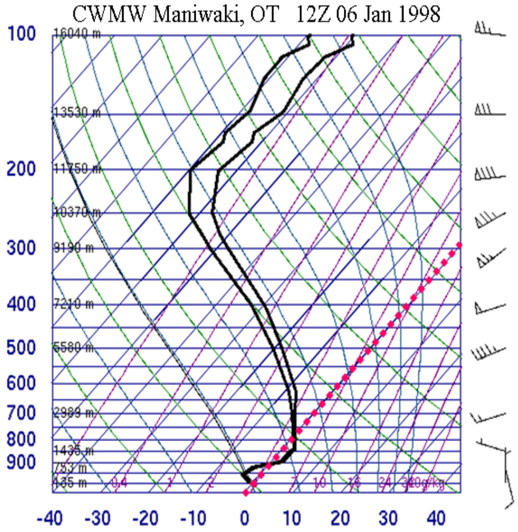

Figure 3. Freezing rain sounding from CWMW. The red dashed line identifies the 0°C isotherm.

3. Forecasting SLD

The Rapid Update Cycle (RUC) numerical weather prediction model (Benjamin et al. 2004) serves as the input to the Forecast Icing Product (FIP; McDonough et al. 2004, Wolff et al. 2006). The RUC has the usual suite of output fields including a five species microphysics package that includes supercooled cloud and rain water. The liquid water clouds in the model always have the same cloud condensation nucleus concentration. Therefore differentiation of cloud drop concentrations by airmass, as shown above, is not yet possible (Thompson et al. 2004).The initiation of the ice phase remains a challenging problem to correctly model. Model microphysical forecasts from the winter of 2005 were compared to several thousand co-located icing pilot reports. The pilot report locations were matched to the closest RUC grid point and they needed to be within 30 minutes of the model valid time. The comparison showed that RUC had frozen and/or liquid condensate forecast at ~60% of the co-located pilot reported icing locations and supercooled cloud water forecast at ~30% of the locations. These results suggest that supercooled cloud water is significantly under forecast by the RUC while the ice phase is over-forecast.

FIP begins its analysis of a model grid point by determining if a cloud layer is present in the model sounding. If a one is found, FIP identifies the likely meteorological scenario present, based the cloud structure and forecast of precipitation (i.e. deep snow producing clouds, freezing rain, no precipitation ...). Icing-specific fuzzy logic membership functions are created using the model output for each level within the cloud layer. The output values from the membership functions are then combined, depending on the meteorological scenario, to produce the icing probability and severity fields. The FIP-SLD algorithm analyzes the model soundings and identifies cloud layers that may be forming SLD through collision-coalescence, freezing rain, or deep convection. The collision-coalescence and freezing rain algorithms are presented below.

3.1 Collision-coalescence SLD

First FIP identifies all the cloud layers and their cloud top temperatures. A new cloud layer is identified when the vertical profile of θ_e indicates an inversion and there is sufficient dry air to prevent snow seeding from the layer above. Once all the layers are identified then the air-mass of the layer is identified as either boundary layer air or non-boundary layer air. Non-boundary layer air is assumed to be clean and will reside within a cloud layer that is isolated from the boundary layer. A 2.5^{o}K or greater inversion over 25mb defines a new layer. Once the air mass of the layer is identified its CTT is examined. If the CTT < -14^{o}C the ice phase is expected and the interest that SLD could form is zero. As the CTT increases to -12^{o}C the interest in possible SLD production increases to a maximum of 1 (see Fig. 4a).

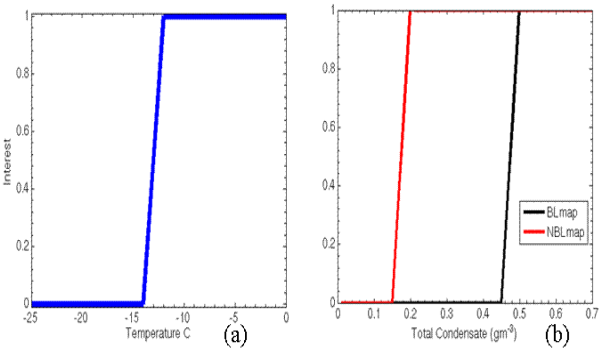

Figure 4. The SLD-CTT interest map (a), BL and non-BL total condensate interest maps.

When the CTT interest is positive (CTT > -14^{o}C) then the mass of the five model condensate species at each model level in the cloud is summed into the total condensate variable (TOTC). If the air mass within the cloud layer is defined as boundary layer air and TOTC < 0.45 gm^{-3} then the TOTC interest is set to zero and SLD will not be forecast. The boundary layer TOTC interest map increases to1 as the TOTC increases beyond 0.5 gm^{-3} (see Fig. 4b). In non-boundary layer air TOTC needs to exceed 0.15 gm^{-3} for a non-zero interest. The interest increases to 1 as the TOTC increases beyond 0.2 gm^{-3} (see Fig. 4b). The RUC supercooled rain water field is the final predictor of SLD. SLD will be predicted if any mass > 0.05 gm-3 is forecast. The interest reaches unity when the mass exceeds 0.1 gm^{-3}. The CTT, TOTC, and model rain interest values are combined into the SLD potential.

Figure 5 demonstrates the FIP_SLD collision-coalescence algorithm. The FIP cloud top is identified at 2600m and has a CTT of -8°C (Fig. 5a). The θ_e profile (Fig. 5b) and its vertical gradient per 25mb (Fig. 5c) identify the top of the boundary layer at 1900m. Since the total condensate (Fig. 5d) exceeds 0.15 g m^{-3} within the non-boundary layer air above 1900m and the CTT > -14°C SLD is forecast to form. The SLD that formed in the non-boundary layer air will then seed the boundary layer cloud. There was no supercooled rain forecast by the RUC. Combining the CTT interest (1), the TOTC interest (1), and the model supercooled rain interest (0) we end up with SLD forecast between 1200 and 2600m.

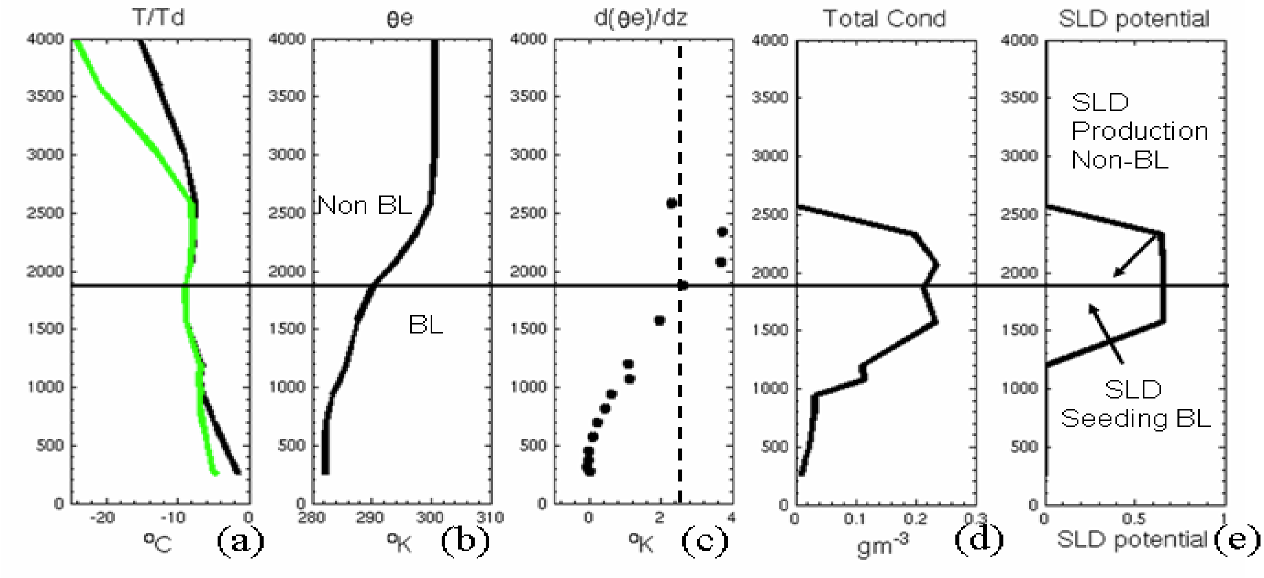

Figure 5. Model sounding (a), θ_e (b), vertical gradient of θ_e per 25mb (c), total condensate (d), SLD potential (e). Horizontal black line identifies the top of the boundary layer, dashed black line identifies the layer detection threshold temperature.

3.2 Freezing rain

The FIP-SLD freezing rain algorithm requires a model sounding indicating a deep single layer cloud with a cold cloud top temperature and precipitation forecast at the surface. Identification of the melting layer and subsequent freezing layer are also required. SLD will be forecast within the subfreezing air beneath the melting layer. SLD would be forecast below 900mb (~3000 ft) if the algorithm was using the sounding shown in Fig 3.

4. Using FIP to avoid SLD icing

Figure 6 shows the plan view of icing conditions at 15,000ft from a 3-h forecast of FIP. The icing probability and icing severity valid at 1800 UTC on 11 Sep 2007 are shown. If a flight was planned between Cleveland, OH (CLE) and Washington D.C (IAD) this view shows that icing might be encountered. The vertical cross-section of the FIP is presented in Fig. 7. The icing probability (top), SLD (middle), and severity (bottom) between CLE and IAD are show. A narrow band of SLD is forecast between 11,000 and 17,000 feet along the west slopes of the Appalachians. The cross section allows the pilot to file a flight plan to minimize time spent in icing conditions and to completely avoid the SLD layers. A possible flight plan would be to climb to 19,000ft out of CLE, fly above the forecasted SLD layer, descend to 10,000ft and continue on to IAD.

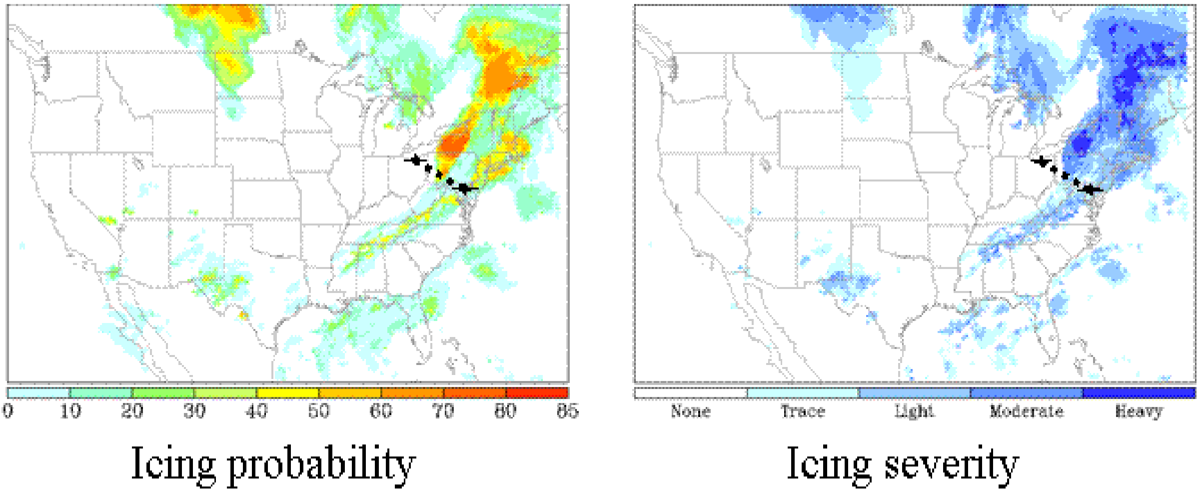

Figure 6. Horizontal view of the FIP icing probability (left) and icing severity (right).The black dashed line identifies the cross section shown in Fig. 7

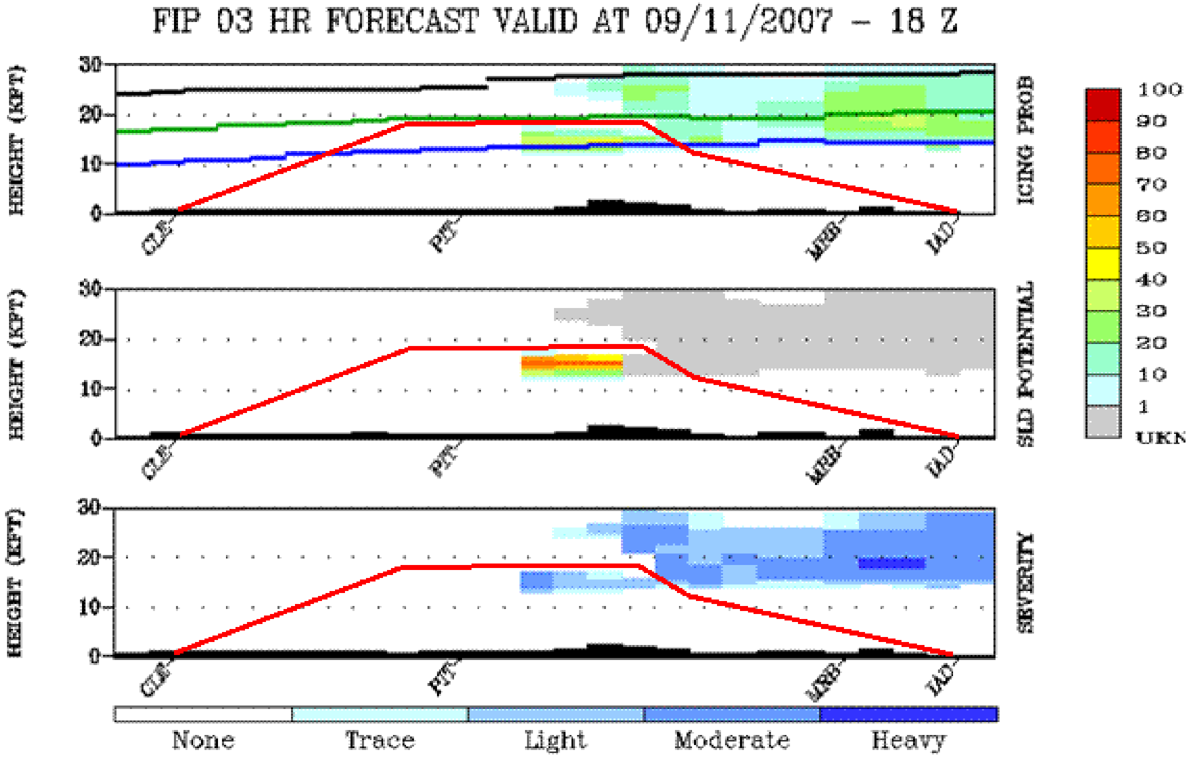

Figure 7. FIP cross section between CLE and IAD. Red line identifies a potential flight plan to avoid SLD icing.

5. Summary

A new fuzzy logic algorithm which forecasts supercooled large drop (SLD) conditions aloft is presented. The algorithm runs as a part of the larger forecast icing product (FIP). The algorithm considers SLD formation within collision-coalescence, freezing rain, and deep convective clouds. The collision-coalescence algorithm identifies the cloud layer's airmass as originating from the boundary layer or above the boundary layer. The airmass type, along with the cloud top temperatures and numerical model condensate complete the forecast. These values are combined using fuzzy logic to create the SLD forecast. The freezing rain algorithm identifies SLD below the melting layer when the vertical structure suggests a surface precipitation forecast of freezing rain. When FIP identifies deep convection SLD is forecast to temperatures as cold as -30°C.

Acknowledgements

This research is in response to requirements and funding by the Federal Aviation Administration (FAA). The views expressed are those of the authors and do not necessarily represent the official policy or position of the FAA.

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